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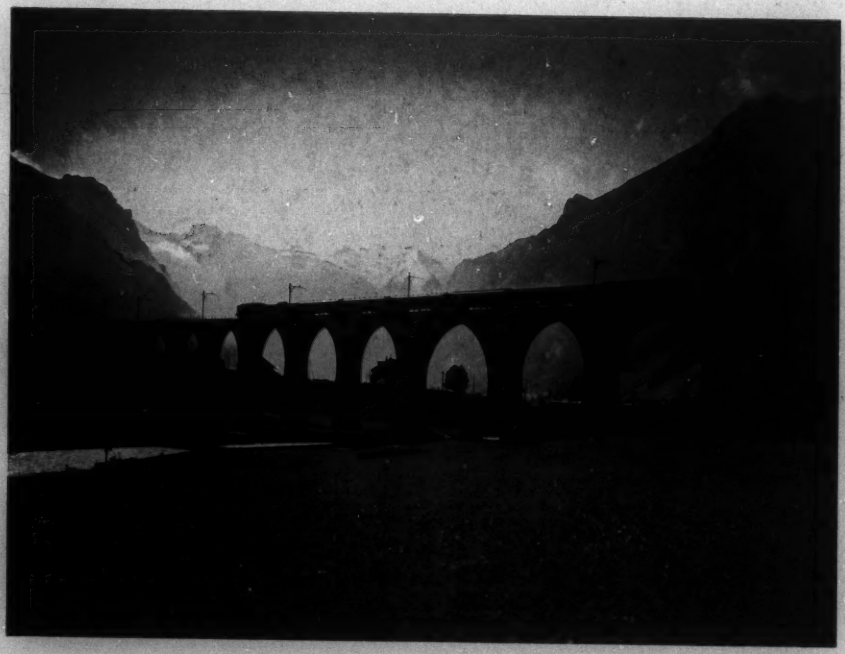

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This Month—

Front Cover

The stately Kander viaduct of the Lötschberg railway in Switzerland is but one of the numerous technical features which distinguish this line, a connecting link between the Bernese Oberland and the Simplon route in the Valais.

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★THESE PAPERS are to be discussed at the forthcoming A.I.E.E. winter convention to be held in New York, N. Y., January 23–26, 1934. The technical program tentatively arranged includes sessions on many subjects of interest to electrical engineers. Symposiums also are being arranged on some of these subjects, and plans for entertainment features are being carried forward. *p. 928–30*

AT A recent discussion of the Engineers' Council for Professional Development held at Cooper Union in New York City, a realization of the true position of the engineer in the existing social order was urged as a basis for a program of united action in improving the professional status of the engineer. *p. 932–3*

THE 50th anniversary of the founding of the A.I.E.E. occurs May 13, 1934. Accordingly, the Institute's board of directors and a specially appointed committee are making plans for a fitting observance of that anniversary. These include a special issue of ELECTRICAL ENGINEERING for next May. *p. 931*

A SYMPOSIUM on switching at modern large generating plants is being arranged for the Institute's 1934 winter convention. Two of the papers in this symposium, describing switching facilities at plants in widely different sections of the country, are included in this issue. *p. 826–30 and 868–75*

COÖPERATIVE study of the joint use of poles for telephone and power service in the Staten Island, N. Y., area indicates that the safety of joint construction with 6,900-volt distribution can be made comparable with that of the 2,300-volt joint construction now existing there. *p. 890–8*

THE action of electric filters may be more thoroughly understood by study of a mechanical analogy which has been developed to show the changes in magnitudes and phase relations of the current passing through a filter. *p. 813–6*

TRANSMISSION line voltages continue to climb, led as before by the pioneering spirit of the West. Spurred by economic and other considerations, and reflecting directly the results of extensive laboratory research, the design for a new 275-kv line to carry power from Boulder Dam to the City of Los Angeles calls for the use of a segmental tubular copper conductor 1.4 in. in diameter. *p. 854–60*

DIELECTRIC research continues to show in its results a close interdependence of physics, chemistry, and practical experience in so far as the evolution of effective, economical electrical insulation is concerned. Current trends and extensive bibliographies are given in 3 reports presented before recent meetings of the N.R.C.'s committee on electrical insulation. *p. 918–27*

ENGINEERING studies of fundamental factors involved in the design of electric energy delivery systems point to the "radial" system as being the best "all-around" system for areas of load densities too low to justify low voltage networks. *p. 831–8*

Sound Measurements Versus Observers' Judgments of Loudness

To test the ability of the "total noise" meter to give proper relative ratings for complex sounds of about the same level, but of materially different quality, a series of tests has been made wherein the noise measurements were compared directly with observers' judgments of loudness. The results showed surprisingly close agreement between the meter readings and the average judgments of a group of observers. The results show also the superiority of noise meter readings over the judgment of any single observer.

By
P. H. GEIGER E. J. ABBOTT

Both of the University of Michigan, Ann Arbor

A TYPE of soundmeter which ordinarily is called a "total-noise" meter has come into extensive use during the past few years. Such a meter consists of a microphone, attenuator, amplifier, rectifier, and indicator meter. The over-all frequency response of the instrument is adjusted to conform to an "equal loudness contour" obtained from published data on psychological tests on a group of human ears (see "Direct Comparison of Loudness of Pure Tones," by B. A. Kingsbury, *Phys. Rev.*, v. 29, April 1927, p. 588). Five sound meters of this type were demonstrated at the Rochester meeting of the A.I.E.E. in May 1931 (see A.I.E.E. TRANS., v. 50, 1931, p. 1041–51; and ELECTRICAL ENGINEERING, v. 50, May 1931, p. 342–4, 349–51) and they are now available commercially from several concerns.

Total-noise meters of this type obviously give a correct indication of the loudness of steady pure tones of approximately the level to which the frequency-response of the instrument is adjusted. In accordance with Definition 3015, *Journal* of the Acoustical Society of America, v. II, Jan. 1931, p. 316, throughout this paper the term "loudness" means "—the magnitude of the sensation produced for the average normal ear." In other words, loudness is not a meter measurement but is the average judgment of a group of observers. Unfortunately, single pure tones are practically non-existent in ordinary experience, and almost invariably the instruments are used to measure complex sounds. The question immediately arises as to whether the meter readings for complex sounds give a suitable measure of the loudness of such sounds as they appear to the average ear. This article describes direct tests between meter readings and the judgments of a group of observers under conditions and for sounds which were essentially practical. The authors were both surprised and pleased with the closeness of the agreement, and the results are presented herewith in the hope that they will be of interest to the various investigators and committees working on this important problem.

Agreement between the loudness as determined by the observers and the total noise as measured by meter was so close that at first it might appear that a total-noise meter would be sufficient for practical purposes of sound and noise study, and that frequency analysis of the sound and measurement of the individual components would be required only for fundamental laboratory investigations. This idea is quite erroneous. In many practical problems, such as machinery noise reduction, for example, frequency analysis is absolutely essential; at the same time, in many laboratory investigations total-noise measurements furnish information that cannot be obtained by analysis. Space does not permit a discussion here of the advantages and limitations of total-noise and frequency-analysis measurements. Both of these types of measurement are used freely in the University of Michigan laboratory; they are not regarded as alternate methods, but as mutually complementary. While the data of this article deal only with total-noise measurements, this does not discount the value of frequency analysis in dealing with most practical problems.

In connection with machinery noise studies in this laboratory the need for supplementing frequency analyses with some sort of single reading representative of the integrated effects of all frequency components present led, in the fall of 1926, to the construction of a total-noise meter. This instrument was of the general type already mentioned. It consisted of a Western Electric condenser type transmitter, single stage preamplifier, volume control, amplifier, weighting network, rectifier, and indicator meter. For obtaining the data used in this paper the weighting network was adjusted so that the over-all frequency response corresponded to Kingsbury's (*loc. cit.*) 60-db equal loudness contour. The indicator meter was a Weston one-milliampere model 301 meter used in conjunction with a vacuum tube with condenser-grid leak rectification. It was recognized that this meter would not follow impulsive sounds; but, as will be explained presently, it was

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Table I—Loudness Ratings by 5 Typical Individual Observers of a Group of 6 Vacuum Cleaners of Different Makes

Order of Rating	Ratings by Individual Observers					Average of 21 Observers
1st (loudest)	*e*	*c*	*a*	*e*	*e*	*c*
2d	*a*	*a*	*e*	*f*	*a*	*e*
3d	*f*	*f*	*c*	*c*	*c*	*a*
4th	*c*	*e*	*b*	*a*	*d*	*f*
5th	*b*	*d*	*f*	*b*	*f*	*b*
6th (quietest)	*d*	*b*	*d*	*d*	*b*	*d*

The highest and lowest ratings of each machine are indicated by ***bold face*** type; cleaners designated by lower case letters.

used with a sound chamber having a rotating reflector so that a large grid condenser was used in order to average out short time variations, and no attempt was made to measure peak values. Tests of the rectifier with combinations of pure tones showed that the same reading was obtained on a steady combination of such tones as was obtained on a pure tone of the same rms value.

For pure tones its readings, of course, agree with Kingsbury's average observer. For complex tones it would not be expected to agree exactly with an observer, because of the peculiar behavior of the human ear in summing loudness components. (See "Relation Between the Loudness of a Sound and Its Physical Stimulus," by J. C. Steinberg, *Phys. Rev.*, v. 26, Oct. 1925, p. 507; and "Loudness: Its Definition, Measurement, and Calculation," by Harvey Fletcher, a paper to be published in the *Journal* of the Acoustical Society of America.) To determine how closely the meter would check with actual observations, the experiments to be described were carried out in 1929.

Comparisons were made between meter readings and the judgments of a group of observers in 3 different experiments:

1. The relative loudness and disagreeableness of the noise from a group of 6 vacuum cleaners of different makes and extremely different qualities of sound.

2. The relative loudness of a group of 6 materially different types of sounds.

3. The loudness of a group of 11 materially different sounds rated against a 1,000-cycle test tone.

Comparison of 6 Vacuum Cleaners

Listening tests of the 6 vacuum cleaners were made in the living room of a typical home. The cleaners were placed in an adjoining room which communicated with the observer's room directly through an archway, and also through a second room with archways to both rooms. The observer could not see the cleaners, but he was provided with a switchboard by means of which he could start and stop any cleaner at will. He was instructed to rate the cleaners in order of loudness, making as many back and forth comparisons as desired. Following this, he was asked to repeat the experiment except that the rating was to be made on disagreeableness instead of loudness. In all, 21 observers were used, 14 men and 7 women. Meter measurements, including both total-noise and frequency analyses were made in the laboratory with standard methods which will be described presently.

The most striking feature of the results is the disagreement between individual observers. In the loudness rating, 14 different groupings were obtained among the 21 observers, and in no case did more than 4 observers make the same grouping. Only 1 of the 21 observers made the same grouping as the average of the group. The disagreements were by no means small as is shown in Table I. Various observers

Table II—Disagreeableness Ratings by 6 Typical Individual Observers of a Group of 6 Vacuum Cleaners of Different Makes

Order of Rating	Ratings by Individual Observers					Average of 21 Observers
1st (most)	*c*	*e*	*e*	*f*	*c*	*a*
2d	*e*	*b*	*a*	*a*	*e*	*c*
3d	*a*	*a*	*f*	*e*	*b*	*a*
4th	*d*	*f*	*b*	*c*	*a*	*f*
5th	*f*	*c*	*e*	*d*	*f*	*d*
6th (least)	*b*	*d*	*d*	*b*	*d*	*b*

The highest and lowest ratings of each machine are indicated by ***bold face*** type; cleaners designated by lower case letters.

Table III—Averaged Ratings of 6 Vacuum Cleaners for Loudness and Disagreeableness

Cleaner	Measured Total Noise, Decibels	Loudness Scores			Disagreeableness Scores		
		Men	Women	Total	Men	Women	Total
c	80.5	72	34	106	72	35	107
e	80.5	70	34.5	104.5	65	33	98
a	76.0	56.5	33	99.5	67.5	28	95.5
f	75.6	41.5	23.5	65	39.5	27	66.5
b	70.6	33	11	54	31	16	47
d	69.8	21	11	32	19	8	27

placed machines *a*, *c*, and *e* in all places from 1st to 4th, machine *f* from 2d to 5th and machines *b* and *d* from 4th to 6th places.

In the disagreeableness ratings, the differences were even greater. A total of 17 different groupings was obtained, and only 3 observers agreed on a single grouping. Typical results are shown in Table II. Machine *a* was rated from 1st to 4th place; machines *c*, *e*, and *f*, from 1st to 5th place; machine *b*, from 2d to 6th place; and machine *d*, from 4th to 6th place.

From these large differences it might appear at first that noise measurements have no meaning, but this is not the case. If these same data are averaged by counting 6 if the machine were rated 1st, 5 if it were rated 2d, etc., the very close check shown in Table III is obtained. It may be observed that machines *c* and *e* measured identically by meter, and that the average rating of the 14 men placed machine *c* slightly above *e*, while the average of the 7 women placed them in the opposite order by a very slight amount. These differences are negligible compared with the differences between other machines, and this check is perfect within the accuracy of measurement. In all other cases, the meter readings, the average score of the men, the average

score of the women, and the combined average agreed perfectly.

In other words, while individual observations have little meaning, the average of one group of observers checked the average of another group very closely, and the meter checked the results of both groups. This shows the immense superiority of meter measurements over the judgments of any single observer no matter how skilled he may be.

It is interesting to note that the combined disagreeableness rating placed the machines in identically the same order as the combined loudness rating, although every individual observer made different groupings. From frequency analyses, which were made of each sound, it is possible to determine just which components were disagreeable to each observer. Space does not permit a discussion of these points, but it appeared that certain observers found the lower frequencies most objectionable, while others found the higher frequencies most objectionable.

In this connection, the authors' experience has been that the most important factor in determining the disagreeableness of a sound is whether or not the observer thinks it should sound the way it does. Often this is entirely unconscious, but it is none the less important.

Comparison of 6 Different Sounds

A second series of comparisons between meter readings and observers' judgments was carried out in the sound chamber shown in Fig. 1. This room is $21 \times 18\frac{1}{2} \times 12\frac{1}{2}$ ft with hard walls, and contains

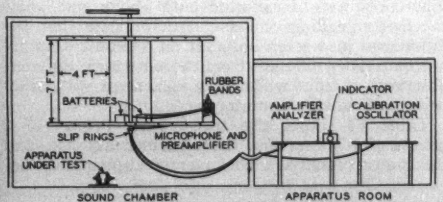


Fig. 1. Diagram of set-up used at the University of Michigan for sound measurement

a large sheet iron reflector which rotates slowly in order to shift the sound wave patterns so that an average value can be obtained. The microphone is carried on the reflector as indicated, and the measuring equipment is located in an adjacent room. Because of the highly reflecting walls and the action of the revolving reflector, the sound pressure, averaged over a short period of time, is substantially the same at each point in the room. For this reason, the relative locations of the observer, the microphone, and the source of sound have no effect on the results. This method was used to insure: (1) that the sound level at the microphone was the same as at the observer; (2) that differences in loudness resulting from phase differences at the observers 2 ears would tend to be averaged out; and (3) that a direct test was made of exactly the method used by the authors for studying machinery noises. Excellent results have been obtained through the use of this method of eliminating the effects of the very troublesome wave patterns that always exist in sound measurement.

Six different sounds were provided, an attempt being made to have them as diverse as possible, and of essentially a practical nature. These were:

a. Ordinary electric buzzer.

b. Ordinary electric bell.

c. Typical vacuum cleaner.

d. Compressed air escaping from a hose.

e. A rattler consisting of a cigar box partially filled with miscellaneous small pieces of metal, the whole being rotated about a horizontal axis at about 100 rpm.

f. A sound generated by the interruption of a 60-cycle supply line by an overloaded raytheon type tube. The resulting voltage was amplified and supplied to a loud speaker. Analysis of the resultant sound showed various amounts of most of the harmonics of 60 cycles between 100 and 1,000 cycles. The speaker characteristics made those in the region of 300 to 600 cycles most prominent.

The observer was placed in the sound chamber and provided with a set of switches that allowed him to start and stop any of the 6 sounds at will. No volume adjustment was provided. The observer was instructed to determine the order of loudness of these 6 sounds, making as many back and forth comparisons as desired. Meter measurements of the levels of the various sounds were made simultaneously with the aural observations. In these tests 20 different observers were used, about $\frac{1}{3}$ of whom had participated also in the tests on vacuum cleaners some months previously.

Here again the differences between individual observers were large; 15 different groupings were obtained, and none of them were the same as the average. Table IV shows a few typical ratings. Sound *d* (air) was rated all the way from 1st to 6th; sounds *a* (buzzer) and *f* (raytheon) from 1st to 5th; sounds *e* (rattler) and *b* (bell) from 2d to 5th; and sound *c* (cleaner) from 4th to 6th.

However, when the combined ratings were computed as before, by counting 6 each time a given sound was rated 1st, 5 when it was rated 2d, etc., the comparison between the meter measurements and the observers' ratings is as shown in Table V. Again the check is perfect. The primary practical requirement for a total-noise meter is to rate properly sounds of essentially the same loudness but of materially different quality. When the extreme differences in the qualities of these sounds and the

Table IV—Loudness Ratings by 7 Typical Individual Observers of a Group of 6 Different Sounds

Order of Rating	Ratings by Individual Observers						Average of 20 Observers
1st (loudest)	*a*	*d*	*a*	*f*	*a*	*a*	*a* (buzzer)
2d	*b*	*f*	*f*	*e*	*e*	*b*	*f* (raytheon)
3d	*f*	*e*	*b*	*a*	*b*	*d*	*e* (rattler)
4th	*e*	*b*	*c*	*b*	*d*	*e*	*b* (bell)
5th	*d*	*a*	*e*	*c*	*f*	*f*	*d* (air)
6th (quietest)	*c*	*c*	*d*	*d*	*c*	*c*	*c* (cleaner)

The highest and lowest ratings of each sound are indicated by ***bold face*** type.

comparatively small range of loudness are considered, the check is truly remarkable. A great many people will hardly detect a change of 1 db in the loudness of a given sound even when the change is made quickly, and an individual often varies by more than 10 db in repeating loudness judgments. The entire range covered by these sounds is less than 11 db and differences of the order of 1 to $1^1/_2$ db are rated accurately by meter in every case.

Comparisons of Loudness Against a 1,000-Cycle Test Tone

About the time the previous test was made, various workers in the field of acoustics were discussing the specification of loudness in terms of the intensity of an equally loud 1,000-cycle note. [Editor's Note: On June 26, 1933, the sectional committee on acoustical measurements of the American Standards Association approved this method as a proposed standard method of determining the loudness of any sound. See "Noise Measurement Being Standardized," Electrical Engineering, v. 52, November 1933, p. 741–6.]

Table V—Comparison of the Ratings of 6 Noises as Given by Meter and by 20 Observers

Noise	Total Noise as Measured, Decibels	Observers' Scores
a (buzzer)	75.8	109
f (raytheon)	73.3	85
e (rattler)	69.9	74.5
b (bell)	69.0	68.5
d (air)	67.6	57.5
c (cleaner)	64.9	25.5

In order to test this method, comparisons were made on the 6 sounds listed in the previous test, together with 5 additional sounds. All of these new sounds were produced electrically and were supplied to a loud speaker in the sound chamber. The reflector was rotated continuously to eliminate errors due to standing wave patterns. The 5 new sounds were:

g. Speech from a phonograph record.

h. Music from a phonograph record.

i. 2,100-cycle note from an oscillator.

j. Sound from raytheon circuit, same as sound *f*, except at lower level.

k. Same as sound *j*, except at a still lower level.

The observer was placed in the sound chamber as before, and was supplied with a double throw switch by means of which he could switch as often as he wished from the sound to be measured to the 1,000-cycle test tone, which was introduced by a loud speaker. He was provided also with a volume control for the 1,000-cycle note; this he was instructed to adjust until the loudness of the test tone was equal to that of the sound being measured. When that setting was obtained, he signalled the experimenter in the next room who then measured the levels of the 2 sounds. The same 20 observers were used for this test as were used for the preceding test. After about a month, measurements were repeated with 10 of the observers on 6 of the sounds.

Again the results show striking individual differences. The average discrepancy between the first and second observations by the same individual was 5.1 db, with individual differences nearly 3 times as great. Table VI shows the maximum and minimum ratings made on each sound, by the same observer at different times (columns 4 and 5) and by the group of observers (columns 2 and 3). On the average, the estimates of the different observers covered a range of about 20 db on each sound, while the variations of single observers covered a range of about 10 db on each sound. In both cases the differences were distributed both above and below the meter readings. These data indicate that the differences in a given observer on different days are not materially different from those between different observers, a point which is in agreement with other tests made in this laboratory.

Table VI shows also the average ratings of 2 groups of 10 observers, the combined average, and the meter readings. The average discrepancy be-

Table VI—Summary of Results Obtained by 20 Observers in Comparing the Loudness of Various Complex Sounds With a Pure 1,000-Cycle Note

Sound	Measured Loudness Level, Decibels	Discrepancies Between Meter and Observers, Decibels*						
		All Observers		Individual		Average of Observers 1–10	Average of Observers 11–20	Average All 20 Observers
		Max. −Db	Max. +Db	Max. −Db	Max. +Db			
Buzzer	76	− 5.4	+ 7.9	−3.9	+6.3	+2.3	+5.4	+3.9
Raytheon (high)	73	− 7.5	+12.8	−7.5	+3.5	+2.6	+3.8	+3.2
Music	72	− 5.7	+ 9.0			+1.9	+5.1	+3.5
Rattler	70	− 7.5	+11.0	−4.4	+7.1	−0.1	+5.3	+2.6
2,100-cycle note	70	−12.3	+11.1			+0.2	−0.6	−0.2
Bell	69	− 8.6	+14.8	−8.6	+4.6	+1.9	+6.2	+4.0
Speech	68	−11.3	+13.3			−0.4	+5.4	+2.5
Air	68	−20.0	+11.0	−3.5	+7.9	−3.2	+2.2	+0.5
Cleaner	65	− 4.3	+12.1	−2.8	+5.3	+1.8	+7.0	+4.4
Raytheon (medium)	60	− 5.0	+11.3			+2.0	+2.2	+2.1
Raytheon (low)	40	− 5.4	+10.3			+1.5	+0.3	+0.9
Averages		− 8.5	+10.4	−5.1	+5.8	1.6	3.9	2.4

*Note: A plus sign indicates that the meter reading of the 1,000-cycle note which the observer judged to be equal in loudness to the sound in question was larger than the meter reading of total noise of the given sound.

tween the meter readings and the combined judgment of the observers is 2.5 db, while the maximum discrepancy is only 4.4 db; this is considerably less than the average accuracy with which a single observer could repeat balances on different days. In view of the large spread of the individual observations, and the differences between the averages of the 2 groups of 10, the check between the meter readings and the observations is well within the accuracy of the average ear ratings. It is felt that this was a very severe test indeed, and that the meter measurements were completely confirmed.

Conclusions

In designing these experiments an attempt was made to test the most practical use of a total-noise meter, namely its ability to give proper relative ratings for complex sounds of about the same level, but of materially different quality. Large differences in level are distinguished easily, and practical cases of single pure tones are essentially nonexistent. [In the case of the one pure tone measured, the authors' data agree with Kingsbury's (*loc. cit.*) to within $\frac{1}{2}$ db]. To this end an attempt was made to simulate sounds similar to those met in practice, and to provide as great differences in quality as possible. In every case the agreement between the meter readings and the average ear ratings was much closer than the estimated accuracy of the latter.

In addition to these specific tests, a total-noise meter of the type described here, with suitable adjustments in frequency response, has been used by the authors for several years for measuring noises ranging from 120 db on some 5,000-hp gear units, to around 20 db on electric refrigerators. This work has involved both comparisons of the loudness of machines of different quality, and determinations of the results of changes in given machines, many of which changes were very small. In all of this work, no cases have been encountered where the instrument readings were inconsistent.

The data here presented indicate that meter readings of sounds with many components have a tendency slightly low, which is in accord with certain experiments recently reported. (See "Loudness: Its Definition, Measurement, and Calculation," by Harvey Fletcher and W. A. Munson, *Journal* Acoustical Soc. of Amer., v. 5, Oct. 1933, p. 82. It appears that appreciable differences may be obtained in special cases such as that of a large number of component musical notes, well separated in frequency, and of nearly the same loudness; but such cases do not seem to occur very often in practice. It may be possible to develop an instrument that will weigh and sum the various components of a complex sound more nearly according to the complicated requirements of the latest theories of loudness summation; but until such an instrument is available in such form that it can compete with the present total-noise meter in simplicity, speed, convenience, and accuracy, the present form of meter seems certain to hold its place along with the frequency analyzer as an essential tool for practical sound measurement.

Filters in Action

Electric filters are used to prevent only currents which are in a desired frequency range from passing through a circuit. Changes in magnitudes and phase relations of the currents passing through a filter occur, and these changes are different for different frequencies. By means of the mechanical analogy described in this article, the action of currents in a filter may be observed and clearly understood.

By
C. E. LANE

Bell Telephone Labs., Inc., New York, N. Y

MODERN long distance communication, both radio and wire, is dependent in a large measure on the electric filter. Invented by G. A. Campbell of the American Telephone and Telegraph Company, the electric filter consists of a group of condensers and coils so connected that they have the property of readily passing alternating currents of certain frequencies, and of greatly attenuating, or weakening, currents of other frequencies. Those most commonly employed may be divided into 3

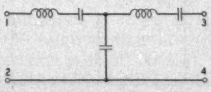


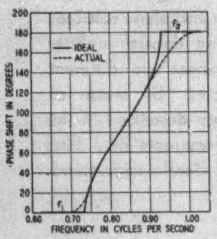
Fig. 1. One form of section for an electrical band pass filter

types: the low pass filter, which passes all frequencies below a stated frequency and attenuates all those above it; the high pass filter, which passes all frequencies above a specified value and attenuates those below; and the band pass filter, which passes all frequencies between values known as the upper and lower cut-off frequencies, and attenuates all those beyond these values.

The unit of filter design is the filter section, of which many different types are possible. A section commonly employed for a band pass filter is shown in Fig. 1. A complete filter will include one or more of such identical sections connected in tandem, and the attenuation for any frequency is the summation of the attenuations of all the sections.

Full text of "Filters in Action" presented at a meeting of the communication group of the Institute's New York Section, Nov. 9, 1933, and published in the *Bell Lab. Record*, v. 12, Sept. 1933, p. 2–7. *Not published in pamphlet form.*

A single section, and thus a complete filter to a greater extent, acts in 2 ways toward alternating currents passing through it. It produces an attenuation and a phase shift—both of which vary with frequency. An ideal phase shift characteristic is shown by the solid line in Fig. 2, and an ideal attenuation characteristic is similarly shown in Fig. 3. The shape of these curves is the same for a section as for a complete filter, but the actual ordinate values are greater for the complete filter in proportion to the number of sections. It will be noticed that for both phase shift and attenuation there is a sharp break in the characteristics at 2 points marked f_1 and f_2, and these are the cut-off frequencies.



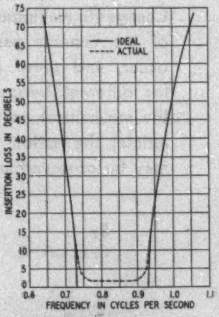


Fig. 2 (left). Ideal and actual phase shift characteristics of a section of a mechanical band pass filter. The electrical analogue of a section of this filter is given in Fig. 1

Fig. 3 (right). Ideal and actual attenuation characteristics for 7 sections of the mechanical band pass filter

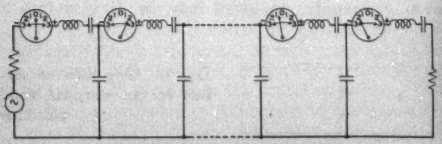


Fig. 4. A band pass filter with meters inserted to indicate the internal operation

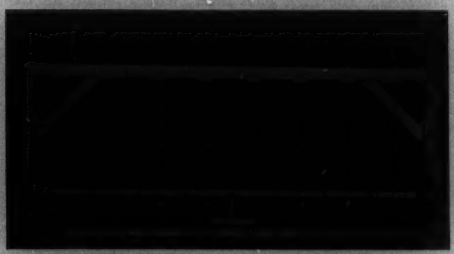


Fig. 5. Operation of the mechanical filter below lower cut-off

Ideal filter action requires that the terminating impedance at the end of a filter be of a definite value, and this value is different, in general, for each frequency. It is not practicable, of course, to provide a terminating impedance that will have the different values required at each frequency. However, by proper filter design the ideal impedance required for terminating the filter may be made nearly a constant resistance over a large part of the passed band. When this is done, the use of a fixed resistance is quite satisfactory. The effect of terminating the filter in such a fixed resistance is to slightly round off the ideal characteristic at the cut-off frequencies, thus giving a characteristic indicated by the dotted lines on the 2 graphs.

Although the characteristics of filters may be completely and concisely expressed in mathematical terms, it would be very helpful if one could actually see the increasing phase shift and attenuation from section to section. In theory a fairly good indirect method of seeing would be to insert meters in a filter as shown in Fig. 4. The variation in excursion or travel of the meter pointers along the length of the filter would indicate the attenuation, and the difference in relative position of the various pointers at any one instant would indicate the phase shift. There is one very obvious difficulty with such a method of watching the action of a filter. If the frequencies were in the voice range or higher, the pointers would move so rapidly that the eye could not follow them. To be able to use this method to advantage the frequencies should be of the order of one cycle per second, but electrical filters for such low frequencies are not practicable.

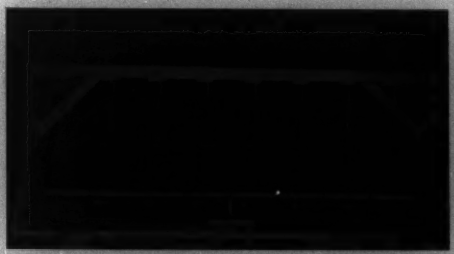


Fig. 6. Just above the lower cut-off the phase shift per section is about 14 deg and there is a slight overall attenuation

Mechanical Filters for Visual Observation

It is practicable, however, to make a filter for such low frequencies by substituting mechanical for electrical elements. Fundamentally, filter action is a

resonance phenomenon, and resonance can be secured mechanically as well as electrically. The action of the pendulum of a clock is a familiar example. A series of pendulums properly connected together may be made to act as a filter, and such an arrangement is shown in the accompanying illustrations. The filter consists of 7 sections of the type shown in Fig. 1.

In this mechanical filter the mass of the pendulum bobs acts as the series inductance, and the attraction of gravity on the bob, as the series capacitance, while the arched spring shown connecting adjacent pendulums serves as the shunt capacitance. The first pendulum at the left is driven from the flywheel of a small motor through a flat spring, and by varying the speed of the motor, the frequency of the mechanical force is changed. A resistance termination is obtained at each end of the filter by allowing the 2 bobs at the ends of the filter to swing through viscous oil.

The amount of swing of the pendulum corresponds to the current flowing in the electrical filter, and the

Fig. 7. In the middle of the pass band there is no attenuation, and the phase shift per section is about 90 deg

attenuation produced by the filter can be observed by noticing the difference in amplitude of swing between the first and last pendulums. Phase shift per section is indicated by the difference in position of adjacent pendulums at the same instant. Since at all frequencies up to the lower cut-off there is little or no phase shift, all pendulums will be in about the same relative positions at the same instant for frequencies below the lower cut-off. Above the upper cut-off, the phase shift approaches 180 deg per section so that when one pendulum is at one end of its swing, the next will be at the other end. Between lower and upper cut-off the phase shift between adjacent pendulums will vary depending upon the frequency.

To show these 2 effects photographically, an exposure of several seconds was made which brings out the total arc of swing of each pendulum. At some instant during this exposure, an instantaneous flash was made which records the position of all the pendulums at the same instant, and thus shows phase shift. The pass band of this mechanical filter is from 0.73 to 0.93 cycle per second and the accompanying photographs show the conditions at and somewhat below the lower cut-off, at and somewhat above the upper cut-off, and in the middle of the pass band.

In Fig. 5 the frequency was 0.68 cycle per second and the large degree of attenuation, about 50 db, is readily evident. Since there are 7 sections this means an attenuation of about 7 db per section, and it will be noticed that the second bob has slightly less than half the amplitude of the first; the third,

Fig. 8. Just below the upper cut-off a slight over-all attenuation is again noticeable and the phase shift per section has increased to 120 deg

half the amplitude of the second; and so on. The motion of the fifth bob is so slight that it is barely perceptible. The phase shift, it will be noticed is zero degrees per section; all pendulums are in exactly the same relative positions.

In Fig. 6 the frequency is about 0.74 cycle per second, just above the lower cut-off. At this frequency the attenuation per section is very slight but is plainly evident for the overall filter. The phase shift is also small, being 14 deg per section. The total phase shift for the entire filter is about 98 deg, and it will be noticed that the last bob is a little over 90 deg out of phase with the first.

In Fig. 7, at a frequency of 0.84 cycle per second, the conditions at about the middle of the pass band is shown. There is no noticeable attenuation; the amplitude of swing of the last bob is almost exactly the same as that of the first. The phase shift per section is about 90 deg. In all cases, each pendulum is about 90 deg out of phase with those on each side.

In Fig. 8 the frequency is 0.90 cycle per second, just below the upper cut-off. Here again, since the frequency is nearly at the cut-off value, some overall attenuation is noticeable but it amounts to only about 5 db. The phase shift per section, however, is in the neighborhood of 120 deg which can be seen by noticing that every third pendulum is in the same relative position.

In Fig. 9 the conditions for a frequency above the upper cut-off—at a value of about 1.00 cycle per second—is shown. Overall attenuation is 50 db, which is so great that no motion is noticeable at the last bob. The phase shift is the full 180 deg per section, which is plainly evident in the photograph.

Reflections and Delay

This series of photographs illustrates phase shift and attenuation at different frequencies, but the

mechanical filter may also be used to illustrate other characteristics such as reflection, which occurs when filters are improperly terminated, and the delay in the propagation of a disturbance through the filter. In Fig. 10 is reproduced a photograph taken for a frequency of 0.84 cycle per second—the mid band frequency of the filter—where the phase shift is 90 deg per section. For this photograph the terminating impedance of the filter was removed, that is, the filter is "short-circuited" at the output end. This gives complete reflection of the wave at the end of the filter. It will be noticed that the amplitude of every even numbered pendulum bob is doubled due to this reflection, the reflected wave being exactly in phase with the direct wave at these positions. On the other hand the reflected wave is approximately 180 deg out of phase at the odd numbered pendulum bobs, and hence the direct and reflected wave nearly cancel each other at these points and the motion is very small. If the frequency were to remain the same and the output of the filter "open-circuited" by holding the last bob still instead of "short-circuited" as in Fig. 10, there would still be

Fig. 9. Above the upper cut-off the large attenuation is evident, and the phase shift per section is 180 deg

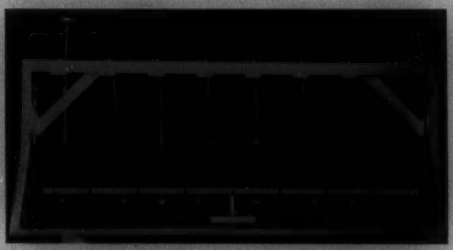


Fig. 10. Illustrating the reflection that occurs with improper impedance termination, in this case a short circuit

complete reflection at the end of the filter. In this case, however, the nodes would appear at the even numbered pendulum bobs instead of at the odd numbered ones as shown in the photograph. Photographs of this kind might be taken at other frequencies and the tesultant motion at any point along the filter would depend upon the relative phases of the direct and reflected waves.

To show the delay in the propagation of a disturbance through the filter the photographs shown in Fig. 11 were taken. The upper one of these photographs shows the motion taking place in the filter during the first half second after starting a disturbance at the input of the filter by displacing the

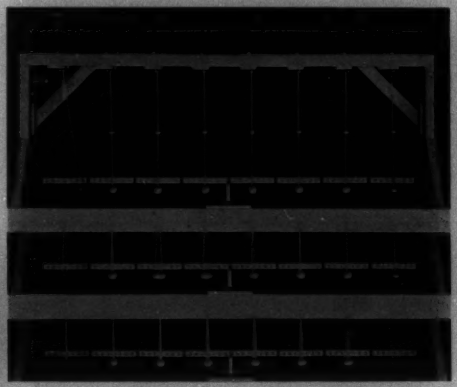


Fig. 11. Illustrating the delay in the passage of a transient impulse through a filter

Above. Transient just starting
Middle. After 4 sec transient is approaching midpoint
Bottom. After 10 sec transient has reached the end of the filter

first pendulum bob and then suddenly releasing it. It will be noticed that during this interval the motion is confined solely to the first section of the filter. The photograph shown in the middle is obtained from an exposure during an interval between the fourth and fifth second after the starting of the disturbance. By this time the disturbance has reached the middle of the filter. The lower photograph shows the motion during the interval between the ninth and tenth second after the starting of the disturbance, by which time the disturbance has been propagated entirely through the filter. In other words the delay of this filter, due to a transient disturbance, is between 9 and 10 sec. If from the middle of the phase shift curve shown in Fig. 2, we compute $\frac{dB}{d\omega}$ where B is the phase shift in radians and ω is 2π times the frequency, and multiply it by the number of filter sections, the value obtained will be about 9.5 sec. This relation holds approximately true for any band pass filter regardless of the nature of the transient disturbance applied at the input of the filter. The disturbance will not arrive at the output of the filter until a time given by the slope of the phase characteristic of the filter in the middle of the band.

The Relaxation Inverter

The characteristics and design of the relaxation inverter, which requires only one tube for obtaining alternating current from a d-c supply, are described in this article. This inverter is simple and reliable and can be made to provide alternating voltage having a good wave form.

By
HERBERT J. REICH
ASSOCIATE A.I.E.E.
University of Illinois, Urbana

INVERTERS for obtaining alternating current from a d-c supply have been developed in 3 principal types, all using the gas or mercury vapor hot cathode electronic tube. The series and parallel types of 2-tube inverters have been developed considerably in the last few years. Recently a third type called the relaxation inverter, and using but a single tube, has been developed; it is described in this article.

An a-c output of 100 watts or more from a relaxation inverter can be obtained with a tube of the *FG-67* thyratron type, with an anode efficiency of 50 to 73 per cent when the inverter is supplied with 115 volts direct current. The maximum power output is approximately proportional to the square of the d-c voltage and within limits is roughly proportional to the frequency and the condenser capacity. The efficiency increases somewhat with the d-c voltage. Very poor voltage regulation and change of wave form with load make this inverter most suitable for service in which the load is constant, or in which poor voltage regulation is an advantage, as in the operation of neon signs. A number of problems are encountered in the design of the relaxation inverter, chief among which are those affecting frequency control, stability, and wave form.

When properly designed the relaxation inverter is simple and reliable and gives unusually good wave form. Useful modifications include a 2-tube circuit which delivers double the output of the single tube circuit, and a "d-c transformer" by means of which it is possible to obtain from 80 to 100 ma at a voltage of from 300 to 500 from a 115-volt supply.

The basic problem involved in the design of inverter circuits is that of finding methods of stopping the flow of anode current without the removal of d-c supply voltage. The series type of inverter depends for its current stopping action upon the natural decay of current during the charging or discharging of a condenser. The parallel type makes use of the surge from a charged condenser in applying a negative voltage to the anode for a sufficient time to allow deionization to take place.[1] The third type, the relaxation inverter, has recently been described by the writer.[2,3] Its action depends upon the oscillatory nature of the discharge of a condenser in a circuit having a high ratio of inductance to resistance. It differs from the series and parallel circuits in that it requires only one tube and that the tube conducts during a portion of the cycle which is normally small compared to the period of oscillation.

Written especially for ELECTRICAL ENGINEERING. *Not published in pamphlet form.*

Basic Circuit of the Relaxation Inverter

The mechanism by which the anode current is periodically stopped, and the action of the grid in developing characteristics which are essential to satisfactory inverter performance, are most readily explained by the aid of a preliminary discussion of the relaxation oscillator circuit of Fig. 1. In order for oscillations to be set up in this circuit it is essential that the tube should fire at a voltage which is greater than the normal anode voltage drop, and the deionization time should preferably be small. When direct current is first applied to the circuit, the condenser C_1 charges at a rate and in a manner which is determined by the supply voltage and the circuit constants. If the ratio of inductance to resistance is high the charging current varies very nearly sinusoidally; if it is low, the condenser current and voltage vary exponentially. Should the tube fail to fire, the condenser would charge to a maximum voltage approximately equal to twice the line voltage in the former case, and equal to the line

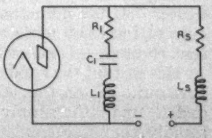


Fig. 1. Relaxation oscillator circuit

voltage in the latter. In general, the graphs of current and voltage variation are exponentials or damped sine waves, the voltage variation eventually approaching line voltage if the tube fails to fire. When the condenser voltage becomes equal to the firing voltage, the tube conducts, allowing the condenser to discharge through the tube, which has negligible resistance when conducting. If the resistance R_1 is small as compared to the inductance L_1, the damping is negligible, and the discharge current varies very nearly sinusoidally. The current which is flowing into the condenser at the instant the tube breaks down transfers to the tube, and subsequently varies in a manner which is determined by the supply circuit resistance and inductance, R_s and L_s. The total current through the tube, therefore, is the sum of the condenser discharge current and the current which flows through L_s

1. For all numbered references see list at end of article.

and R_s. The action of the inductance L_1 causes the condenser to continue to discharge to a negative voltage which, neglecting damping, equals the original positive voltage less the constant anode drop through the tube (about 10 to 15 volts). The condenser current then reverses and the net current

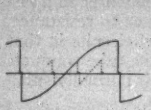


Fig. 2. Time variation of condenser voltage, showing increase of period resulting from increase of firing voltage

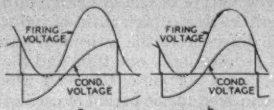


Fig. 3. Control of oscillation by means of combined d-c and a-c grid voltage

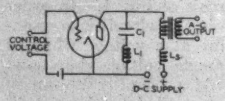


Fig. 4. Simple grid-controlled relaxation inverter

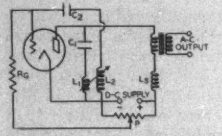


Fig. 5. Self-excited relaxation inverter

through the tube becomes the difference between the coming from the d-c supply and that from the condenser. If the inductance L_1 is small the condenser current increases more rapidly than the supply current through L_s, and eventually becomes equal to it. At this instant the anode current is zero, and the tube goes out. If, on the other hand, L_1 is large and L_s and R_s small, the supply current may build up more rapidly than the condenser current, preventing extinction of the tube. By using a low value of L_1 the natural period of that branch of the circuit may be made so short that the condenser discharge and extinction of the tube take place in less than 0.001 sec. A small L_1 also results in a discharge current the amplitude of which may be 15 or 20 times the maximum supply current, so that the condenser current becomes equal to the supply current, and thus extinguishes the tube, before the negative condenser voltage has decreased appreciably. Consequently at the instant the tube is extinguished the condenser and d-c supply voltages are additive and tend to increase the initial supply current. The condenser recharges to a positive voltage and the cycle repeats. After the first cycle, because of the initial negative condenser charge and the initial supply current, the condenser would charge to a voltage greater than twice line voltage if the tube were prevented from firing. The deionization time of the tube, of course, must be less than the time taken for the condenser voltage to change from its initial negative value to a positive value equal to the normal anode voltage under load (10 to 15 volts).

A certain amount of a-c power may be drawn from the condenser branch of the circuit by coupling to L_1, but the resulting damping is detrimental to the action of the circuit and may result in stopping of oscillation. Better results are obtained when power is drawn from the supply branch, either across the inductance L_s or from a transformer in series with or replacing L_s. Mathematical analysis of the circuit shows that the maximum power output at a given frequency increases very rapidly with increase of either d-c supply voltage or firing voltage. Because of the low firing voltage of the 2-element hot-cathode arc rectifier tube, the power output is ordinarily small. The low firing voltage has other disadvantages. It gives a comparatively low ratio of peak condenser current to peak supply current so that the tube may fail to go out at the end of the condenser discharge when a-c power is drawn from the circuit. It also reduces the charging time of the condenser to a fraction of the time which would be taken if the condenser were to charge to its maximum value before breakdown of the tube, and thereby limits the period of oscillation to a value which is small compared to the natural period of the circuit. It is therefore impossible to reduce the frequency under load below about 150 cycles without the use of an excessive amount of capacity.

Function of the Grid in the Relaxation Oscillator

It is evident that in order to obtain substantial power output at commercial frequencies it is necessary to raise the firing voltage of the mercury vapor rectifier tube. This may be accomplished either by means of a grid maintained at a constant negative potential or by means of a constant magnetic field at right angles to the flow of current from anode to cathode. In Fig. 2 is shown the large increase in period which may be obtained by increasing the firing voltage to a value equal to the maximum voltage to which the condenser will charge, which is normally about twice line voltage in an inverter which is delivering rated power. The increase of period results both from the increase of positive condenser voltage and from the corresponding increase of maximum negative voltage. The dotted curve shows the variation of condenser voltage for a low firing voltage. The tube will obviously be permanently extinguished if the firing voltage is increased beyond the maximum voltage to which the condenser will charge.

The use of a constant negative grid voltage or a constant magnetic field to increase the firing voltage has 2 disadvantages. The first results from the small slope of the condenser voltage curve near the maximum. A slight variation of supply voltage, firing voltage, or load results in a large variation of frequency, or even in permanent extinction of the tube. The second difficulty results from the fact that during the first cycle after the d-c voltage is applied the maximum voltage to which the condenser

can charge is lower than during succeeding cycles. If the firing voltage is high enough to allow full charging of the condenser after equilibrium is established then the tube will not fire at all. These difficulties may be prevented by applying, in addition to the d-c grid voltage or steady magnetic field, an a-c voltage or field of desired frequency, the peak value of which is considerably in excess of that necessary to raise the firing voltage to a value equal to the maximum condenser voltage. The curve of firing voltage then intersects the curve of condenser voltage at a large angle, so that small variations of supply or control voltage or of load have little effect upon the value of condenser voltage at which the tube fires. The frequency of oscillation is obviously the same as the control frequency. By proper adjustment of circuit constants and control voltages or fields the firing voltage may be made to equal the condenser voltage at the instant that the condenser is fully charged, as indicated in Fig. 3*a*. If the charging time of the condenser is less than the period of the control voltage, the firing voltage may become equal to the condenser voltage after the condenser is fully charged, as in Fig. 3*b*. The condenser will then start discharging back into the line before the tube fires, and the initial condenser current at the time of firing will be negative.

Simplest Grid-Controlled Inverter

The circuit of the simplest form of grid-controlled relaxation inverter is shown in Fig. 4. The necessary grid excitation may be supplied by any type of oscillator, by a standard a-c supply, or may be fed back from the output through a suitable phase shifting circuit. An air core reactor of about 1.3-mh inductance made up of No. 10 wire wound in optimum inductance shape has been found to give most satisfactory results for L_1. A capacity of from 10 to 40 μf is used for C_1, the exact size being somewhat dependent upon tube, frequency, and load. By using a small capacity, and hence a natural frequency which is high compared to the excitation frequency, several condenser oscillations may be made to occur for each cycle of the output. This is ordinarily not desirable since it results in very poor wave form of output voltage. The inductance L_s is necessary under heavy load, due to the reduction of transformer inductance, and is frequently desirable at light loads in improving wave form, as will be explained later. A tube of the type known as *FG-67* thyratron gives excellent results in this circuit. The filament may be heated from the d-c supply in starting and later transferred to the output. A tube with a 110-volt heater is, of course, more satisfactory.

At first glance the circuit of Fig. 4 may appear to be similar to that of the tuned arc. There are, however, a number of essential differences, the most obvious of which is the control of the tube by means of a grid or magnetic field, resulting in reduction of frequency without the use of excessively large condensers, in stability of frequency, and in great increase of power output. The second important difference lies in the fact that in the tuned arc the power is drawn from the condenser branch of the circuit, whereas in the relaxation inverter it is drawn from the d-c supply branch. This eliminates from the output voltage the high peak which would be obtained during the discharge of the condenser were the power taken from the condenser branch, and thereby improves the wave form. Lastly, although it is possible to produce relaxation oscillations in the tuned arc circuit, those which are ordinarily desired are undamped sinusoidal oscillations. It is interesting to note that the function of the tube and the inductance L_1 in the inverter circuit is to cause a rapid reversal of charge and voltage of the condenser C_1, so that it can again be charged to a positive voltage from the line.

Self-Excited Circuit

A self-excited circuit which gives excellent results is shown in Fig. 5. L_2 is an air-core inductance having a comparatively large number of turns, which is coupled to L_1. The discharge of C_1 through L_1 induces in L_2 a high voltage which causes a momentary flow of current through the tube by way of the grid and thus charges the condenser C_2. At the end of the discharge of C_1 the tube has ceased to conduct and, because of the rectifying action of the grid, the negative charge on the grid and condenser cannot leak off through the tube. Consequently the grid has a high negative potential which prevents the tube from firing until the charge on the condenser has leaked off through the high resistance R_g. The frequency depends upon the circuit constants and may be readily adjusted by varying the coupling between L_1 and L_2, the value of R_g or the setting of the potentiometer P. Making the slider of the potentiometer more positive increases the rate of change of grid voltage at the instant of firing and therefore improves the constancy of frequency. Hence the potentiometer may be omitted and R_g connected directly to positive side of the line. Equally good results are obtained by coupling L_2 to

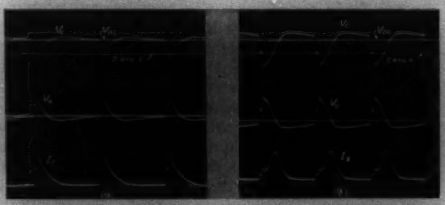


Fig. 6. Oscillograms of condenser voltage, output voltage, and supply current; supply circuit reactor, L_s, omitted

(a) Heavy load (b) Normal load

L_s. By a proper combination of the 2 methods of grid coupling the frequency may be made practically independent of load variation. L_2 also may be replaced by the secondary of the output transformer. It is not necessary to make use of the rectifying property of the grid, since the rectification may be

Fig. 7 (left). Oscillogram of condenser voltage, output voltage, and supply current at normal load, showing improvement of output wave form resulting from the addition of a 0.1-h air-core reactor (L_s) to the supply circuit

Fig. 8 (right). Oscillogram of condenser voltage, output voltage, and supply current under light load, using L_s, a 0.1-h air-core reactor, as in Fig. 7

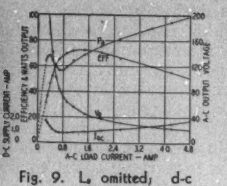


Fig. 9. L_s omitted; d-c voltage = 113 volts; C_1 = 40 μf; 75-cycle output; resistance load; type *FG-67* thyratron tube

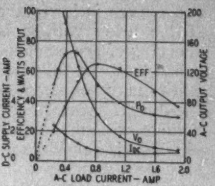


Fig. 10. Air-core reactor of 0.07-h inductance and 3-ohms d-c resistance used for L_s; d-c voltage = 113 volts; C_1 = 40 μf; 75-cycle output; resistance load; type *FG-67* thyratron tube

Figs. 9 and 10. Variation of power output, efficiency, output voltage, and d-c supply current with a-c load current

accomplished by means of an auxiliary rectifier or an auxiliary anode in the tube. In this manner it is possible, in fact, to employ an external grid tube in the inverter.[3,4]

Inverter Performance and Design of the Output Circuit

In Fig. 6 are shown oscillograms of condenser voltage, supply (transformer primary) current, and output voltage obtained with a self-excited inverter of the type shown in Fig. 5, without the use of the induetance L_s. Oscillogram *a* was taken under heavy load. Because the inductance of the heavily loaded transformer is small, the condenser charges exponentially, and the resulting output voltage has poor wave form. Oscillogram *b* was taken under medium load. The effect of increased transformer inductance is evident. The oscillograms of Fig. 7 show the great improvement in wave form of output voltage resulting from the introduction of a 0.1-h reactor L_s in series with the transformer primary. On open circuit, or under light loads, it is sometimes found that, although the primary current wave may appear to have excellent wave form, the output voltage has very poor wave form. The reason for this quickly becomes apparent through a study of the transformer vector diagram and an analysis of the circuit. Under normal loads the reactive component of the primary current is small compared to the load component, and the secondary voltage is very nearly proportional to the primary current. On open circuit, on the other hand, the primary current is mainly reactive and the secondary voltage is proportional to the rate of change of current. Hence under light load any small irregularities of primary current which occur during the discharge of the condenser may be associated with large changes in voltage. This is clearly indicated by the oscillogram of Fig. 8. For this reason it is best, so far as wave form is concerned, to design the transformer so that its inductance under load is small, and to provide the necessary supply circuit inductance by means of the series reactor L_s.

Typical Curves

In Figs. 9 and 10 are given typical curves of power output, efficiency, secondary voltage, and d-c current as functions of a-c load current for pure resistance load. The a-c currents were measured by means of a thermo-ammeter and at each load the load resistance was measured by means of a wheatstone bridge. Power, efficiency, and secondary voltage were computed from these measured data. A 40-μf condenser was used for C_1 and the frequency was kept constant at 75 cycles. The curves of Fig. 9 were obtained without the series reactor L_s and those of Fig. 10 with an air-core reactor of 0.07-h inductance and 3-ohms d-c resistance. It should be noted that the current scale in Fig. 9 is double that in Fig. 10. The series reactor causes a marked falling off in power output, efficiency, and terminal voltage with load. I^2R loss in the reactor entirely accounts for the lowered efficiency at light load, and partially at the larger loads. It is evident that in determining the size of the reactor L_s it is necessary to weigh the relative importance of stability and wave form on one hand, and efficiency, power output, and voltage regulation on the other. The poor voltage regulation of this type of inverter, both with and without L_s, is explained by the fact that the power output is limited at any given frequency and capacity.

The curves of Figs. 9 and 10 were obtained with an output transformer of 1:1 ratio. Those for a transformer of ratio $1:n$ may be derived from the curves of Figs. 9 and 10 by dividing the current scale by n and multiplying the voltage scale by n. In designing an inverter for a specific application it is necessary to use a transformer ratio which will give the correct voltage at the desired power output.

The power output is very nearly proportional to the square of the d-c voltage, and the efficiency increases somewhat with d-c voltage. Within limits the power output is roughly proportional to the capacity and to the frequency.

To prevent "motor boating"[3] it is necessary to design the grid circuit carefully. Best action appears to be obtained with a small grid condenser (0.1 μf or less) and a large grid leak (100,000 ohms or more). Too large a condenser and too small a leak result in motor boating and in excessive power loss in the grid circuit.

Modifications

Fig. 11*a* shows a modified form of the relaxation inverter which may be made self-exciting by the methods already outlined. Because the air-core reactor L_1 is here replaced by the larger inductance of the primary of the output transformer the circuit is not so stable as that of Fig. 4, and the wave form is much less desirable. The output voltage is distorted because of the relatively slow discharge of the condenser and because the induced voltage depends not only upon the supply current, but also upon the condenser discharge current. Fig. 11*b* shows another form of circuit which will give stable oscillations. It may be made self-exciting by any of the methods which have been described, and power may be drawn from the inductance or from a secondary coupled to it. A simple and practical modification of this circuit is shown in Fig. 11*c*. The inductance L' is necessary under heavy load and may be used at light loads to improve wave form. To prevent the reduction of grid control voltage with increase of load it is sometimes better to derive this voltage from a separate coil coupled to L', instead of from the transformer secondary. In this type of circuit the condenser charges suddenly through the tube and discharges slowly through the transformer and L'. A theoretical explanation of the operation of the circuit presupposes the presence of inductance in series with the d-c supply which causes the condenser to charge above line voltage, with subsequent reversal of condenser current and extinction of the tube. Practically, no special inductance need be used, the small inherent inductance of the supply branch being sufficient. The addition of a small air-core reactor in series with the d-c supply may be beneficial in preventing too high peak tube currents. When such a reactor is used the circuit becomes in some respects similar to one described recently by Livingston and Lord.[5] The Livingston-Lord circuit, because of resistance in the supply branch and across the condenser, is limited in output and efficiency. An improved form of their circuit which is capable of delivering considerable power at higher efficiency is that of Fig. 11*d*.

A third type of circuit which under proper conditions will oscillate in a stable manner is shown in Fig. 11*e*. A theoretical analysis (considering circuit resistance) readily shows that when voltage is first applied to the circuit the current in the primary of the coupled circuit is a damped oscillation superposed upon an exponentially increasing current. With small damping and close coupling the direction of the current may actually reverse, causing the tube to go out. The coupling would have to exceed 70 per cent with zero damping and because of circuit resistance and power delivered to the load must be considerably higher in any practical circuit. The coupled inductances may be the primary and secondary of a power transformer, the power being drawn from either primary or secondary. Any of the methods of grid excitation are applicable.

A 2-Tube Circuit

A 2-tube circuit which has the advantage of doubled output is shown in Fig. 12. It may be made self-exciting by using the output voltage to excite the grids. At first thought it would appear to be a simple matter to self-excite this circuit by the method employed in the single-tube circuit of Fig. 5. It is extremely difficult, however, to make both branches of the circuit oscillate at the same frequency, and, when synchronized, the 2 tubes tend to fire simultaneously, resulting in practically zero output. The reason for this difficulty lies in the fact that each tube conducts for only a brief portion of the cycle, and there is no sudden change in voltage or current in one branch of the circuit which can be used to fire the tube in the other branch at the proper instant. The wave form obtained with the 2-tube circuit is less satisfactory than that obtained with the single-tube circuit.

Another useful modification of the relaxation inverter makes possible direct transformation of direct current from low to high voltage. There are a number of equally satisfactory forms of such a "d-c transformer" circuit, one of which is shown in Fig. 13. The condenser C_3 is charged from C_1 through the rectifier tube to a voltage which approximates the peak voltage of C_1. It may be readily shown[3] that when the ratio of inductance to resistance in the supply branch of the circuit is high the peak voltage of C_1 may be many times the d-c supply voltage. No difficulty is experienced in obtaining 80 to 100 ma at 300 to 500 volts from a 115-volt

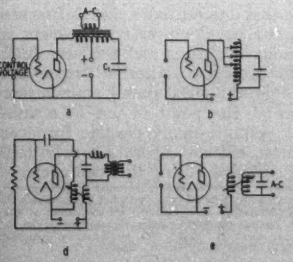


Fig. 11. Other types of relaxation inverter circuits

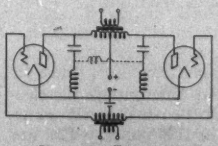


Fig. 12. Two-tube relaxation inverter circuit

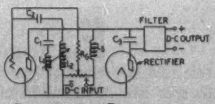


Fig. 13. "D-c transformer" circuit

source with a tube of the type *FG-67* thyratron. With this tube it is also possible to use a 32-volt supply.

Conclusion

The relaxation inverter is simple and reliable and, if properly designed, can be made to provide alternating voltage of fair wave form. Used with a tube of the *FG-67* thyratron type on a 115-volt d-c supply it will deliver 80 watts with an anode circuit efficiency of 50 per cent at 60 cycles. At 75 cycles it will deliver 80 watts at approximately 70 per cent efficiency or 100 watts at 50 per cent efficiency. Between 200 and 300 watts at efficiencies ranging up to 75 per cent can be obtained at 60 cycles from a 230-volt d-c supply. Since the power output goes up as the square of the d-c voltage it is evident that considerable power can be developed at high voltage, the principal problem being that of economical high voltage condenser design. Because of poor voltage regulation and the variation of wave form with load it seems likely that this type of inverter will find its principal application in installations which require fairly constant a-c power, as in the operation of radio receivers and neon signs. The poor voltage regulation is an advantage in neon sign service since the starting voltage of the neon tube is considerably higher than the operating voltage.

A study of the relaxation inverter at higher voltages and with reactive loads is at present being made by L. E. Wetherhold, who assisted in obtaining the curves and oscillograms which appear in the present article.

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Transformers for Electric Furnaces

Important features that should be considered in designing transformers for supplying power to electric furnaces, are pointed out in this paper. The extremely high secondary currents and low secondary voltages, together with the wide variation in voltage required by many furnaces, demand special design considerations in both the transformer and its associated equipment.

By
H. O. STEPHENS
MEMBER A.I.E.E.

L. S. SCHELL, JR.
ASSOCIATE A.I.E.E.

Both of the General Electric Co., Pittsfield, Mass.

FACTORS that differentiate the electric furnace transformer from the usual power transformer are outlined briefly in this paper. The low secondary voltages with their high currents and the large tap range require special design consideration. The important advantages of the conservator transformer would appear to justify its more general use for electric furnaces.

Reactance requirements of furnace transformers are frequently different from those of the usual power transformer, and a separate reactor with taps may be required; this may be mounted either externally or within the transformer case. Strictly straight-line volt-ampere characteristics of reactance, while desirable, are not absolutely necessary; and if iron core reactors are used, the permissible deviations from straight-line volt-ampere characteristics should be specified.

To supply the wide range of voltages required by many furnaces, a method of delta-Y switching with taps in both the transformer and reactor may be used. The advantage of providing this as an integral part of the transformer should not be overlooked. When many tap changes during a heat are desirable the advantages of the "load ratio control" transformer should be carefully considered.

Design Features

The chief feature that differentiates electric furnace transformers from the usual power transformers is the very low secondary voltages and the very high secondary currents required. Another important difference is that while the usual power transformer must deliver power at the point of use at a substantially constant voltage, many electric furnaces require that for most efficient operation definitely varying voltage be supplied during the load cycle.

Full text of a paper recommended for publication by the A.I.E.E. committee on electrochemistry and electrometallurgy, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–26, 1934. Manuscript submitted Oct. 5, 1933; released for publication Oct. 23, 1933. *Not published in pamphlet form.*

The very high secondary currents present a serious problem in the design of large furnace transformers. The low voltage winding must be subdivided into several multiple coils, and the coils and connecting leads must be arranged so that the reactance of each is substantially the same. In the larger sized transformers in the medium primary voltage range, this result can be accomplished best by the use of an interleaved arrangement of windings.

Furnace transformers usually require a number of taps for varying the secondary voltage. Since there are only a few effective turns in the low voltage windings, and since the currents are so high, it is generally necessary to place the taps in the high voltage winding; overwinding it so as to give the required voltage range in the secondary. This means that since the primary turns are varied for each secondary voltage, the flux density in the core varies for each tap connection. The highest secondary voltage determines the size of core, and the lowest determines the total primary turns. Therefore, the range of secondary voltage has a large effect on the total weight and cost of the transformer.

The secondary voltage range also influences the reactance characteristics of a transformer. In a well designed transformer the reactance varies inversely as the square of the secondary voltage. In the usual design it is not desirable to allow a reactance in excess of 15 per cent. A large tap range then may mean that the lowest secondary voltage influences its coil arrangement. A minimum tap range means a minimum sized transformer.

Arrangement of the coils should be such that the primary taps can be located so as to affect the reactance of each of the multiple coils in the low voltage winding substantially equally. A common method of accomplishing this result is shown in Fig. 1. Each group of the high voltage winding is wound for full voltage, and all groups are connected in multiple. The taps are taken from the center of each group, and all corresponding taps are connected in multiple and brought to a single ratio adjuster for quick changing. In Fig. 2 is shown a very high current furnace transformer with the secondary coils arranged in multiple and Fig. 3 shows the high voltage side of the same transformer with the multiple connected taps from each group of the winding. This arrangement insures that the reactance of each of the multiple coils of the low voltage winding will be as near alike as it is physically possible to build them.

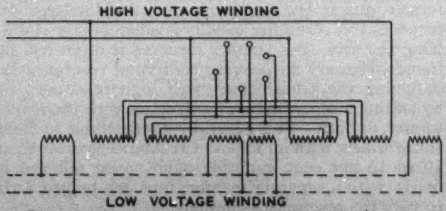


Fig. 1. Arrangement of windings in an electric furnace transformer so that taps in the high voltage winding affects the reactance of each coil in the low voltage winding approximately the same

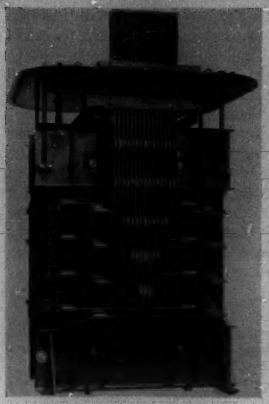
A criticism that might be directed against the type of transformer shown in Figs. 2 and 3 is that the bars leading from the bottom coils are several feet longer than those leading from the top coils and that this might cause sufficient difference in the reactance of the various circuits to cause serious unbalance in the current in the coils, thereby resulting in an increased copper loss and nonuniform heating in the coils. With suitably interleaved bars properly arranged this objection is of no practical importance as is shown by the following calculations and tests:

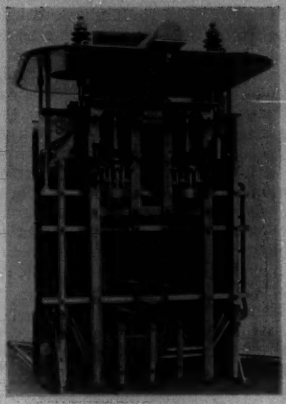
Transformer winding impedance	3.68%
Average impedance of bars	0.27%
Impedance of shortest pair of bars	0.19%
Impedance of longest pair of bars	0.33%
Total impedance of transformer, average	3.94%
Total impedance of longest circuit	4.01%
Total impedance of shortest circuit	3.87%

Maximum variation in impedance from the average is 0.07 per cent, which is less than the possible mechanical variations in the build of the coils and insulation. This would not cause an observable increase in the copper loss, and the expected difference in temperature rise above surrounding oil between the coil with maximum reactance and the coil with minimum reactance would be less than 1 deg C. Tests by means of thermocouples on the various coils showed the observed temperature differences to be no greater than the probable errors of observation. The observed rise of the top coil above the surrounding oil was 15.8 deg C and of the bottom coil 15.1 deg C.

Transformer tanks, covers, and coil clamping structure generally are made of steel. With currents of many thousands of amperes to be brought out, it can be appreciated that great care must be exercised in arranging the bars and leads from the windings and bringing them through the cover so as to avoid excessive losses and heating in the surrounding magnetic materials due to leakage flux from the bars. To do this it generally will be necessary to keep the bars subdivided in accordance with the transformer coil arrangement and interleaved so that the currents in adjacent bars are of opposite polarity.

Most large arc furnaces operate from 3-phase power; it is common practice to supply this power by means of one 3-phase transformer with the low voltage winding arranged for delta connection. Many years ago it was not uncommon for furnace engineers to request that the delta connections be made within the transformer case bringing out terminals so that the furnace operator would have only simple connections to make to his furnace flexible leads. Such an arrangement for furnaces of any considerable size would result in prohibitive losses in the tank and cover of the transformer. Consequently, it is now common practice to bring the interleaved bars through the cover from each phase of the transformer, the purchaser forming the delta external to the transformer in the most suitable place. Where there is a considerable distance between the transformer and the furnace, it is good practice to





Figs. 2 (left) and 3 (right). Assembled core and coils of an electric furnace transformer rated at 25 cycles, 5,000 kva, 13,200/130 volts; (left) low voltage side and (right) high voltage side

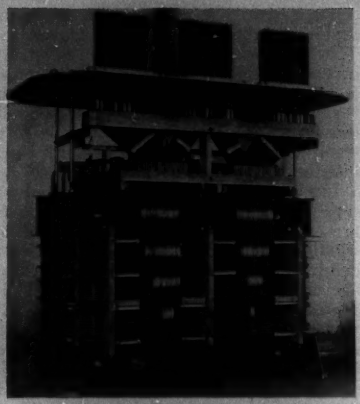


Fig. 4. Assembled core and coils of a 60-cycle 6,600-kva 44,000/170-volt furnace transformer, from the low voltage side; note arrangement of bars

carry the interleaved arrangement of bars just as they come from the transformer as near to the furnace as possible before forming the delta. In spite of the greater total current to be carried by the bars, this arrangement will result in no increase in bar copper, and generally less bar loss and almost complete freedom from losses and heating in adjacent magnetic material. Figure 4 shows a good internal arrangement of bars on a 3-phase furnace transformer.

Water cooled transformers generally are to be preferred for large furnaces, first, because of the saving in initial cost and required space, and second, because an adequate supply of cooling water generally has to be available for cooling the furnace electrode holders and the provision of water for cooling the transformers does not present an additional problem. When the water supply is of doubtful purity, self-cooled transformers should be used.

Furnace transformers often are installed in dirty locations where there is much dust, often of conducting material. It is important that the transformers be well sealed so that this dust cannot enter them. The large number of low voltage bars that must be brought through the transformer covers presents an opportunity for many small dust leaks unless properly designed. Stuffing boxes around each bar give effective protection against the entrance of foreign material.

Because of the difficulty and expense of making the many low voltage bar leads oil tight, oil conservators have not been used generally for furnace transformers. However, it would appear that furnace transformers need the protection afforded by the oil conservator more than the average transformer for the following reasons: (1) The conservator insures absolute immunity internally to dust and dirt; (2) furnace transformers in general are likely to be operated at relatively high load factors, and the conservator is particularly valuable in preserving the oil and preventing sludging; (3) the short periods of shut down between loads cause a considerable amount of breathing which presents an opportunity for bringing moisture into the tank; (4) the long periods of idleness during periodic relining of the furnace give further opportunity for moisture absorption. The oil conservator perfectly protects from all of these conditions. Suitable bus bar bushings have been designed and several furnace transformers have been built with conservators. It would appear that the advantages to be gained are important enough to justify more general use of the oil conservator on furnace transformers.

Reactance Requirements

The arc furnace has a characteristic peculiar to all electric arcs in that the resistance of the arc decreases as the current increases. The arc therefore is unstable unless sufficient constant impedance is placed in series with the supply voltage. There is usually a considerable amount of reactance in the furnace and its connections, in the furnace transformer, and in the supply circuit; and for large arc furnaces this reactance usually is adequate for stabilizing the arc. For smaller furnaces it often will be found necessary to provide additional reactance by designing the transformer with high reactance, or by adding a separate reactor in series with the transformer, or both. It is generally not desirable to build transformers with an inherent reactance greater than 10 to 15 per cent and this value, once selected is fixed; with a separate reactor, taps can be provided to vary the reactance as desired.

The total reactance in series with the circuit determines the power factor. It is desirable to keep the power factor high, but in general little is to be gained by maintaining it above 95 per cent. From

Fig. 5 it may be observed that with a total reactance of 30 per cent the power factor will be above 95 per cent, and the possible short circuit current with an arc resistance of zero (for example, when the electrodes are in contact with the metal) and ignoring all other resistance in the circuit, will be $3^1/_3$ times normal. This figure is based upon the assumption that the volt-ampere characteristic of all reactance in the circuit is a straight line, which is true with the exception of what may be obtained by means of an iron core reactor. From a practical operating standpoint it is of little moment whether the maximum possible short circuit current is $3^1/_3$ times or $3^2/_3$ times normal. Assume, for example, that the total reactance at normal current is 30 per cent and that of this, 15 per cent is supplied by the transformer, the furnace, and the circuit, while 15 per cent is supplied by an iron core reactor. Assume that the characteristics of the reactor are such that $3^2/_3$ times normal current may flow during a short circuit. Then at $3^2/_3$ times normal current there will be a total reactive drop across the transformer, furnace, etc., of 55 per cent, and across the reactor of 45 per cent. Characteristics of such a reactor are shown in Fig. 6; this particular reactor may be said to have an 18-per cent deviation from straight line volt-ampere characteristics at $3^2/_3$ times normal current. This is important because the permissible deviation from straight line volt-ampere characteristics determines the core density that the manufacturer must use in iron core reactors and affects their size and cost. Therefore, if iron core reactors are specified, the permissible deviation from straight line volt-ampere characteristics must be specified. If air core reactors of the current limiting type are specified, their characteristics always should be straight lines and no further consideration need be given to the subject of deviation.

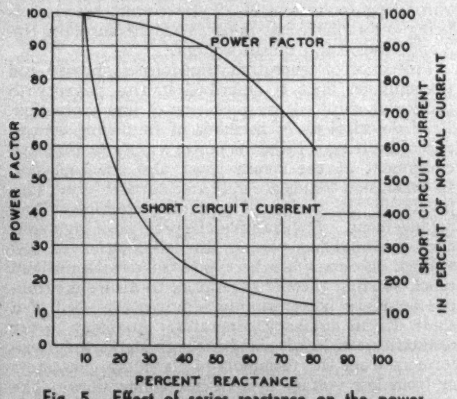


Fig. 5. Effect of series reactance on the power factor and short circuit current of a furnace circuit, straight line reactance characteristics assumed

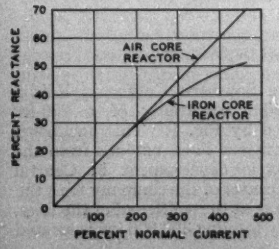


Fig. 6. Characteristic curve of an iron core reactor showing deviation from that of an air core reactor

Delta-Y Switching Arrangement

Most furnaces require a variable voltage for their operation. This is particularly true of the arc furnace for melting cold steel scrap, which usually requires a much higher voltage during the melting down period. Transformers for such furnaces commonly are provided with switches for connecting the high voltage winding in either delta or Y. At the start of a heat the high voltage winding is connected in delta, and after the melt is well under way it is connected in Y so as to give about 58 per cent voltage on the furnace for the refining period. If the Y-delta switches are mounted separately from the transformer, considerable wiring is required and only 2 voltages are available; they can be made an integral part of the transformer, and the very obvious advantages of doing this should not be overlooked in preparing specifications. These switches are available for various combinations of connections, but the majority of furnace transformers in the past have used a 4-position switch. Two delta tap voltages and two Y tap voltages usually are specified. By means of terminal board connections between the taps in the transformer windings and the switch, and also between the taps in the reactor winding and the switch, a choice of several transformer voltages and several values of reactance may be made available. If the reactor is required in the Y connection as well as in the delta connections, the switching arrangement will be complicated unless a 2-winding

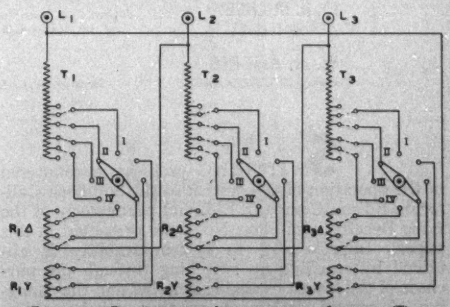


Fig. 7. Connections between transformer (T) 2-winding reactor (R) and delta-Y switch for 2 delta and 2 Y positions. Positions I and II are for delta connections; III and IV, Y connections

reactor is used, one winding for the delta connections and the other for the Y connections, each of which may be provided with taps as required. The Y tap connections need not correspond to the delta tap connections, and an exceedingly flexible choice of reactance is thereby available. In Fig. 7 is shown a diagram of such a delta-Y switch arrangement.

These switches may be operated by a motor mechanism with control button and position indicator on the operator's control panel, or they may be hand operated with a handwheel located on the panel or on the transformer. The motor operated switch, however, is preferred. In all cases the control should be interlocked with the primary oil switch as these delta-Y switches are designed for operation only with no voltage applied to the transformer.

It is permissible to shut down most furnaces for short periods during the heats to change taps. For that reason "load ratio control" transformers designed for changing taps without interrupting the load have not been used extensively. However, if any advantages can be obtained in the operation of furnaces by changing the voltage without interrupting the load, or if more than the 4 operating voltages obtained by the delta-Y switching are required, then "load ratio control" transformers should be considered to determine if their extra cost is justifiable.

Switching at Long Beach Plant No. 3

A study of the connections and methods of operation of the Long Beach steam plant No. 3, part of the system of the Southern California Edison Company Ltd. gives considerable information on desirable methods of switching at modern large generating plants. This paper, part of a symposium on switching at modern large generating plants, presents the problems for one plant.

By

A. A. KRONEBERG, ASSOCIATE A.I.E.E. — Southern Calif. Edison Co. Ltd., Los Angeles, Calif.

O. R. BULKLEY, ASSOCIATE A.I.E.E. — Southern Calif. Edison Co. Ltd., Los Angeles, Calif.

W. A. ANDREE, ENROLLED STUDENT A.I.E.E. — Stanford Univ., Calif.

SWITCHING problems encountered in the operation of the system of the Southern California Edison Company Ltd. and particularly of the Long Beach steam plant No. 3 are presented in this paper. Improvement in system stability is obtained by speeding up switching through the purchase of the fastest available switches and the changing of certain details on existing switches. The magnitude of short-circuit currents is controlled through the sectionalized operation of the system interconnections. Special attention also is given to methods of regaining stability after synchronism has been lost. Results of extensive klydonograph investigations indicate that switching surges can be reduced if the transformer banks are energized and deënergized from the low voltage side. Synchronizing by means of 220-kv circuit breakers is being accomplished at Long Beach steam plant No. 3 and other points on the system.

Protection of generators, transformers, busses, and transmission lines is described in this paper with particular emphasis on problems of line protection. Brief descriptions of methods of frequency control and of insuring continuous power supply to auxiliary equipment at the steam plant also are included. In conclusion trends are indicated toward future simplicity in the design of switching equipment and arrangement. For example, the practice of high voltage synchronizing permits the elimination of low voltage oil circuit breakers, and the development of quick starting turbine-generators to insure continuous auxiliary power supply removes the need of a shaft driven auxiliary generator. Auxiliary power ordinarily can be obtained through stepdown transformers from the terminals of the main generators or from low voltage system interconnections. The greatest change which is indicated for the future is in the high voltage interconnection with the system, whereby the development of high speed single line protection will reduce installation costs, improve reliability of service, and facilitate control of short-circuit currents.

Full text of a paper recommended for publication by the A.I.E.E. committee on power generation, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–26, 1934. Manuscript submitted Oct. 13, 1933; released for publication Nov. 3, 1933. *Not published in pamphlet form.*

General Description of System

The system of the Southern California Edison Company Ltd. consists essentially of a 220-kv backbone, as indicated by Fig. 1. This backbone, composed of 3 transmission lines, extends from the Big Creek hydroelectric development in Central California to the load center of the company with the Long Beach steam plant at the south end of the lines. Hydroelectric capacity totaling 398,000 kw is located

at Big Creek and 200,000 kw of steam generating capacity is tied directly to the 220-kv transmission lines at Long Beach. Seven substations are located along the 220-kv backbone with transformers stepping voltage down to 66 kv, which is the sub-transmission voltage used on radial feeders from the major stations. Some 92,000 kw of stream flow hydroelectric capacity is scattered over the system and tied to the lower voltage networks.

The Long Beach steam installation is composed of 3 plants. Plant No. 1 was started in 1911, has 6 units ranging from 6,000 to 20,000 kw, and a total capacity of 70,000 kw. The generators are operated in parallel on an 11-kv bus and 3 transformer banks are used for interconnection with the 66-kv busses of plant No. 2. Plant No. 2 was started in 1925, has 2 units of 42,500 kw and one rated 60,000 kw for a total capacity of 145,000 kw. The generators in this more modern plant are operated as units with their transformers to a 66-kv bus.

Plant No. 3 was started in 1928, and is at the present time composed of 2 100,000-kw generators, wound for 16,500 volts and connected as units with their transformers. These 2 units are operating in parallel on a 220-kv bus, as indicated by Fig. 2. Some of the outstanding features of the Long Beach steam plant No. 3 of the Southern California Edison Company Ltd. are as follows:

1. All high voltage busses, switches, and transformers are located outdoors. Generators and transformers are arranged on the unit plan, and a double bus structure and duplicate switches are provided for each line and generating unit.

2. Methods and apparatus for accurate frequency control and for insuring continuous power supply to auxiliary equipment have been developed in the course of operation of the Long Beach steam station.

3. The outstanding feature is the magnitude of the ultimate installation and its interconnection with the system. With an ultimate capacity of 800,000 kw planned for the Long Beach steam plant, serious consideration had to be given to control of short-circuit currents. The rapid growth of the system of the Southern California Edison Company Ltd. in the period of years from 1923 to 1930 when the peak load increased from 295,000 kw to 583,000 kw created similar problems which had to be solved with a minimum of expenditures.

During periods of abundant water supply for the operation of hydroelectric plants the steam station becomes a peak and standby plant. During low water periods, the steam station becomes a base load plant.

Since the existing installation in Plant No. 3 is composed of 2 generating units and 2 transmission lines there are few switching problems encountered in its operation. The sections of transmission lines between the Long Beach steam station and Lighthipe, LaFresa, and Laguna Bell substations are so short that the switching problems of the whole group should be considered, especially since the bus and switching arrangement in all of them is essentially the same.

Stability

Stability of operation during short circuits on any system depends to a very large degree upon the speed of switching. This fact is well recognized by the industry and every effort is being made to build faster switches. The policy of the Southern California Edison Company Ltd. is to buy the fastest available switches for future installations and an extensive program of speeding up the switches on existing facilities is under way. Deion grids are being adapted to old Westinghouse oil circuit breakers, stronger trip coils are made to replace the original ones. In some instances the opening time of old 220-kv oil circuit breakers was reduced from 20 to 8 cycles by using 25-amp (d-c) trip coils instead of 5 amp ones, by shortening the travel of the tripping plungers, and by moving the tail stop springs to aid in tripping instead of closing.

Restoring Operating Conditions

Hand in hand with the problem of maintaining stability on the system comes the problem of restoring normal operating conditions after synchronism has been lost. When instability occurs as an aftermath to a short circuit, it is usually the hydroelectric plants that are out of step with the balance of the synchronous machines. In a case of this kind the operators at either Lighthipe or Laguna Bell substation sectionalize their 220-kv busses, separating the steam station from the system with as much load as the former can carry. After

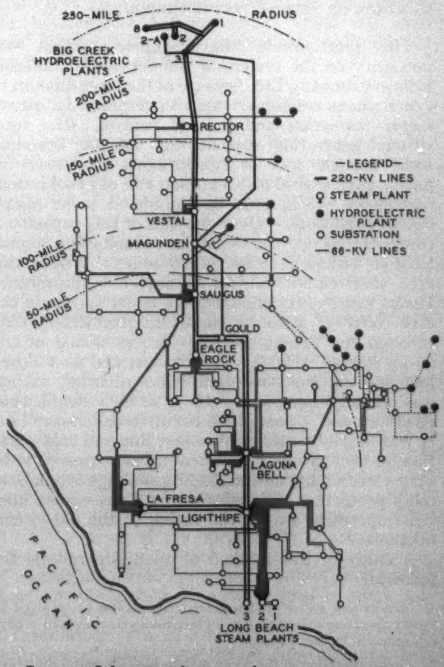


Fig. 1. Schematic diagram of transmission system of the Southern California Edison Company Ltd.

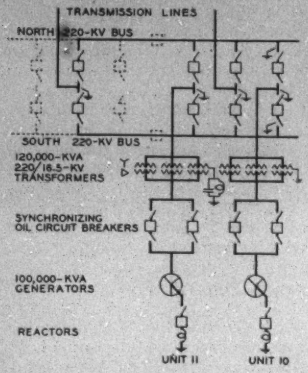


Fig. 2. Single line wiring diagram of the main circuits of Long Beach Steam Plant No. 3

normal speed and voltage have been restored on the 2 separate sections of the system, the operator at the point of separation parallels his busses with the aid of a synchronoscope. The exact point of separation is established beforehand and is determined by generating capacity on line at the Long Beach steam station and loads on transformer banks at the nearest 220-kv substations.

Control of Short-Circuit Currents

The short-circuit kilovoltampere control was necessary on the system of the Southern California Edison Company Ltd. because of the large amount of synchronous condenser capacity required for power factor correction and voltage control. The total system generating capacity of 950,000 kva and some 550,000 kva of synchronous condenser capacity gave a total of 1.5 million kva of synchronous machinery which must be considered under short-circuit conditions. Over one-half of this capacity is concentrated at the 5 major distributing points located within a radius of 20 miles. Within this area short-circuit control became a real problem. It was met by sectionalizing the 66-kv system in the area into 4 major groups, interconnected only through the 220-kv system. Sectionalizing of the 66-kv system which previously operated as a closed loop was accomplished easily since each key station was already equipped with a flexible double bus structure and a pair of oil circuit breakers per line. It was largely a matter of proper line and load selection for each group. This arrangement proved to be very satisfactory in line loading, voltage regulation, relay protection and reduction of short-circuit kilovoltamperes to within the rating of the old circuit breakers.

A study of this method of operation reveals the following:

1. Almost any degree of short-circuit control can be obtained by simply operating a number of small interconnections instead of large concentrated blocks of power.

2. Group operation of the 66-kv system has eliminated the heavy short circuits that formerly caused instability of the 220-kv system and thereby has greatly improved the quality of service.

3. Oil circuit breaker failures have been practically eliminated and the cost of overhaul and maintenance reduced to a minimum.

4. Group operation has simplified dispatching to such an extent that it is possible to dispatch all operations through the medium of switching centers in each group, thereby reducing delay in restoring service following an interruption.

5. Considerable improvement was obtained in the performance of protective relays.

Switching Surges

The installation of reactors or impedors in neutral connections to ground of star connected 220-kv transformer windings was part of the program of limiting fault currents. A General Electric impedor was connected in the neutral of the second unit at Long Beach steam plant No. 3 (unit No. 11). Reactors were similarly connected in the neutrals of 2 75,000-kva banks at LaFresa and one 75,000-kva bank at Laguna Bell. Klydonographs were connected to the 220-kv lines and across one of the reactors at LaFresa in order to investigate the magnitude of lightning surges. So little lightning disturbance has been experienced that the main interest in the results obtained has been in switching surges. It became apparent at once that transient waves of voltage occurred that considerably exceeded the rated voltage of the transformer windings, particularly at the neutral ends. A very considerable reduction in surge value resulted when transformer banks and lines were switched in such a manner as to always open a parallel on the 220-kv side and effect the energizing or deënergizing on the low voltage side. A similar investigation was made at the Long Beach steam station. The results of klydonograph investigations together with recorded rushes of ground current when transformer banks were energized from the high voltage side prompted the adoption of a policy to reduce to a minimum switching operations involving energizing of transformers from the 220-kv busses.

Synchronizing

The 2 100,000-kw units at the Long Beach steam plant are equipped with fast closing synchronizing circuit breakers between the generators and the transformer banks. Installation of these low voltage breakers was made necessary by the difficulty of obtaining potential for synchronizing on the 220-kv side. Potential transformers for 220 kv would have been too expensive and impractical, while potential devices connected to condenser type bushings at the time were new and untried. Potential networks composed of a small transformer and a network of resistance, reactance, and condenser which are connected to a 4,000-volt tap brought out of the condenser type bushing were first used to obtain voltage readings on the 220-kv lines. Over 2 years of satisfactory operation indicated that they could be used on the transformer 220-kv breakers to obtain synchronizing potential at a relatively small cost.

A series of tests was conducted at the Long Beach steam station late in 1930 to determine the feasibility of synchronizing large turbine-generators by means

of slow closing 220-kv oil circuit breakers. The results of the tests were very satisfactory and as a consequence potential devices were installed on all circuit breakers and all synchronizing was subsequently performed on the high voltage side of the transformer banks.

Experience in synchronizing by means of 220-kv oil circuit breakers obtained during the last few years indicates that in future installations of generating units composed of one generator and its transformer bank the 2 may be tied together with no low voltage breaker between them. As previously described, the operators at Laguna Bell or Lighthipe sectionalize their 220-kv busses during cases of loss of synchronism. When normal conditions are restored on the separate sections of the system they must be paralleled with minimum of time lost. The operator has no direct control over the speed of the 2 sections and must issue orders to the faster group to lower its speed to that of the slower one and then parallel his busses whenever the 2 sections are operating at approximately equal speeds and are nearly in phase. The success of this operation depends largely on the good judgment of an operator.

Protection of Generators and Transformers

Both generators and transformers at the Long Beach steam plant are equipped with standard types of differential protection. Percentage differential type relays are used with both generators and the transformers of unit No. 11 while standard overcurrent relays are used with the bank of unit No. 10. The transformer differential relays trip all high and low voltage oil circuit breakers of the unit, and the generator field circuit breaker. A differential operation of the generator relays trips the low voltage breakers, the field breaker, a breaker in neutral connection to ground, discharges tanks of carbon dioxide into the enclosed ventilating system of the generator, and trips the motor driven air blowers. An atmosphere of 25 per cent carbon dioxide can be maintained for 30 min. No overload protection is used with the units to avoid trip-out on loss of synchronism. Past experience indicated that overload relays invariably operate on loss of synchronism and since separation is made at the substations it was desired to keep the units on the line during out of step conditions.

The differential protection of transformers is not sensitive enough to detect insulation failure between turns. In several instances failures of this kind caused considerable damage before a sufficient number of turns were short-circuited to cause a differential operation. Two methods of short-circuited turn protection are used at Long Beach. The low voltage windings of unit No. 10 transformers are composed of 2 coils connected in parallel. The currents of both coils of the winding are balanced in a percentage differential relay. Short-circuited turns in the transformers of unit No. 11 are detected by coils inserted between the windings and the core so that their axis is at right angle to the axis of the windings. These detector coils operate a current differential relay. Both arrangements of short-circuited turn protection trip the same switches that are tripped by transformer differential relays.

Since turbine-generators have an inherently low zero phase sequence reactance it was found advisable to install current limiting reactors in the neutral connection to ground of the generators, and in order to provide adequate protection against faults to ground on the delta connected low voltage side of the transformers, overcurrent relays were connected in the neutrals. These relays also trip the same breakers as the differential transformer protection.

Protection of Busses

Each bus or section of bus where busses are sectionalized by means of oil circuit breakers is equipped with 3-phase differential protection. The bus differential type of protection used by the Southern California Edison Company Ltd. has a perfect record of 100 per cent correct operation. It consists of parallel connection of current transformers in each phase of incoming and outgoing feeders and an overcurrent relay with a very low time and current setting. Any type of short circuit or fault is detected by such an arrangement and all oil circuit breakers connected to the bus are tripped. Unless both busses are involved, no interruption to service results. Differential protection is unquestionably the best method of protection in existence but unfortunately the very nature of its connections limits its application to equipment located at one station. The problems of line protection would not exist were simple differential protection applicable to widely separated terminals.

Protection of Transmission Lines

Double circuit transmission lines are used for 220-kv transmission as well as for the more important 66-kv feeders. It was possible then to obtain high speed of clearing faults through the use of balanced line protection. A current balance type of relay is used with each pair of lines and it is connected to detect unbalance of residual (or ground) currents in the lines. In addition to balanced protection each line is equipped with a separate residual overcurrent relay which is operative whenever one of the transmission lines is taken out of service. The inadequacy of the latter has been illustrated by several cases of system disturbance which resulted when short circuits occurred on single lines.

The use of residual currents for both the balanced and single line protection is due to the fact that in past years nearly 90 per cent of all line faults were single conductor to ground resulting from insulator flashovers. A relay system initiated by residual currents is considerably more sensitive to this kind of fault than are relays operated by phase currents. Efforts have been directed toward the development of additional protection to take care of multi-phase short circuits and some reliable form of single line protection.

Installation of instantaneous 3-phase overcurrent relays on all 220-kv and 66-kv lines at major substations of the company is under way at the present

time in order to provide protection against short circuits not involving ground return currents. The application of this type of relay is limited as it has a definite current setting and no time characteristic. The little experience gained so far shows that these relays provide adequate protection against severe 3-phase and phase to phase short circuits. The undesirable sequence relaying is still present however and will not be completely eliminated until an adequate high speed single line protective scheme is perfected. The ideal high speed single line protection would be one nearest approximating the simple differential protection of busses and equipment, that is, one that balances the output of the line against the input. Numerous pilot wire and carrier current protective devices have been recently proposed and a number of them are on trial at various stations of the company. It is too early to draw conclusions from these trial installations. Suffice it to say that when a reliable and relatively simple single line relaying system is perfected it will eliminate the problem of protection as a factor in the design of high voltage transmission.

Frequency Control

Strict requirements of a constant frequency for the sound motion picture industry and the appearance of electric clocks on the market prompted the development of equipment for accurate speed regulation on the system of the Southern California Edison Company Ltd. The problem was complicated by nature of the company's load, sudden swings of some 10,000 kw being a rule rather than an exception. Equipment has been developed that controls the speed of the system within a fraction of a cycle and compensates automatically for any deviation which may creep in so as to maintain an average frequency of exactly 50 cycles over longer periods of time. The general method of frequency control is to operate all but one of the power plants at constant load (blocked) and have one plant or generating unit operating under automatic frequency control. When a sufficient change in load on the regulating station takes place manual readjustment of loads on other stations is performed to operate as near to best efficiency as permissible under these conditions.

Auxiliary Power

An important item in the operation of steam stations is a reliable supply of power for auxiliary equipment. This power is normally supplied from a small generator coupled to the shaft of the main generating unit. Operation of plant No. 2 during sustained heavy overloads showed that when the speed of the main turbine-generators dropped so did the frequency and voltage of the auxiliary system with consequent disturbance of functions of pumps and other auxiliary apparatus. In order to insure adequate auxiliary power supply during emergencies 3 quick-starting turbine-generators were installed in plant No. 2 and plant No. 3. These turbine-generators can be started from standstill and thrown on the line in 13 sec. The switching over of the auxiliary load from the normal source of supply to the emergency turbine-generator is done automatically from one control button. During the switching operation the auxiliary power busses are deënergized for less than 0.5 sec. The motor driven exciters of the main generators are also equipped with steam turbines which have a governor setting slightly below normal speed, thus insuring continuous excitation for the main generators.

Conclusion

In concluding it will be well to indicate some of the trends in the design of the steam station and its interconnection with the system. As a direct result of the practice of high voltage synchronizing the elimination of low voltage oil circuit breakers was made possible. The development of quick starting turbine-generators to insure continuous auxiliary power supply removes the need of a shaft driven auxiliary generator. Auxiliary power can be readily obtained through stepdown transformers from the terminals of the main generators or from low voltage system interconnections. The greatest change by far would be in the high voltage interconnections with the system. In the original plans the ultimate 800,000-kw steam plant was to be connected to the Lighthipe substation through 4 220-kv transmission lines and pairs of lines from Lighthipe were to feed LaFresa and a future substation to the east of Lighthipe. The development of high speed single line protection will make it possible to loop the 2 future lines through LaFresa and the future substation, thereby saving the cost of installation of 4 line positions on the Lighthipe 220-kv busses, providing for reliability of service and facilitating control of short-circuit currents. The busses at the Long Beach steam plant No. 3 will be sectionalized with 2 generating units and a transmission line to each section. Such an arrangement will permit operation of the 220-kv system in a manner similar to the one used on the 66-kv system of the company. It will be possible to operate Long Beach as 4 separate steam plants of 200,000-kw capacity interconnected through several transformer banks in series. Thus the transmission lines and transformers will be operating in parallel to the load and in series to a short circuit.

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Fundamentals of Design of Electric Energy Delivery Systems

Fundamental economic factors involved in the design of systems for delivering electric energy to typical urban load areas are discussed and analyzed in this paper. The fundamental principles presented already have been applied in a practical way in the design of a radial system recently built in Buffalo, N. Y. Engineering studies upon which the selection of that system was based led to the conclusion that for areas of load densities too low to justify a low voltage network, a properly designed radial system is likely to be the most economical and satisfactory system.

By
J. ALLEN JOHNSON
FELLOW A.I.E.E.

R. T. HENRY
FELLOW A.I.E.E.

Both of the Buffalo, Niagara & Eastern Pwr. Co., Buffalo, N. Y.

DELIVERY of electric energy to consumers from a generating or receiving station within a load area embraces 3 steps, namely, subtransmission, substations, and distribution. In considering the cost of such delivery, all of these steps must be included; and in applying the fundamental principles involved in the design of a delivery system, a proper economic balance should be established among these 3 elements for best over-all results.

Development of automatic equipment, eliminating the need of operators in substations, has opened the way for the attainment of an ideal balance of cost of these 3 elements, thus making possible a rational design for minimum over-all delivery system cost. At one extreme may be found relatively short subtransmission lines, large substations, and long distribution feeders. At the other extreme the subtransmission lines may be carried clear to the distribution transformers, eliminating the substations and distribution feeders entirely as is done in the low voltage network system. Between these 2 extremes an infinite number of combinations is possible. As the subtransmission lines are extended further toward the consumer the substations become smaller and closer together and the distribution feeders shorter. For every value of load density there is probably one theoretically most economical combination. Practically, the requirements usually may be handled economically by 2 such combinations: a low voltage network for high density commercial sections, and a system of small substations with relatively short 2.3/4-kv distribution feeders for the remainder of the area.

For the 2.3/4-kv distribution system 2 alternative connection schemes are available: the network scheme, and the radial scheme. From an analysis of comparative costs, advantages, and disadvantages of each, the conclusion is reached that for large areas, at least, the radial scheme besides being less costly is more flexible and economically adaptable to growth and changes in load conditions.

Proper application of these fundamental principles results in the simplification of substation design, with consequent reduction of cost. In this connection, the "firm rating factor" also is important in determination of system design; the use of small units increases this factor and thereby tends to reduce cost.

Practical application of the fundamental principles discussed is illustrated by the radial system recently designed and built in Buffalo, N. Y., this type of system having been selected after comparisons with alternative intermediate voltage network systems had been studied for the same load area. The general conclusion reached as a result of those studies is that for areas of load densities too low to justify a low voltage network, a radial system properly designed in accordance with the principles outlined is likely to be the most economical and satisfactory system.

Distribution Terms Need to Be Defined

In these critical times it seems particularly necessary, if misunderstanding and misinterpretation by critics of electric power companies are to be avoided, to define meticulously the terms used in any statements made by the engineers of those companies. The term "distribution" especially is one that has been used somewhat loosely. Specifically, this term is applied to that part of the electrical system lying between the outgoing terminals of the distribution substations and the ingoing terminals of the consumers' premises. In its broadest aspect, however, distribution embraces the entire plant and process involved in the transportation of electric energy from the point of its production to the points of its use. In the modern large power system

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this process ordinarily takes place in 3 distinct steps, namely:

1. From generating stations to large receiving stations located in the area to be served. This step variously is called "high voltage transmission," "main transmission" or just "transmission." The receiving station sometimes is called a "terminal station"; sometimes a "type *A* (to *Z*) substation," a "main substation," a "transmission station," a "transmission substation," or by some other name particularly appealing to the individual concerned.

2. From the receiving station to the distribution substations. This step, originally called "transmission" before the advent of high voltage transmission, now usually is called "subtransmission."

3. From the distribution substations to the consumers. This step is that specifically known as "distribution."

In view of the lack of standardization of terms to designate the several parts of the process and system as indicated, perhaps power system engineers have only themselves to blame if some of their critics persist, as they seem to do, in misunderstanding the fact that the distribution substation and the transmission substation are 2 distinct and separate entities and not one and the same. When (and if) such critics finally do recognize this fundamental fact perhaps then they will desist from their present practice of implying that the entire cost of "electricity" is the "gateway" cost plus the "distribution" cost, and in their speeches and publications will take some account of the influence of "subtransmission lines" and "receiving stations" on the cost of electric service.

During the last few years leading power system engineers, recognizing the existing confusion of thought and nomenclature, and reflecting the current shift in emphasis and point of view from generation to distribution, have been thinking not in terms of generation, transmission, and distribution, but in terms of "load area" systems and the "bulk power" system; that is, in terms of delivery within, and supply to, given load areas. The individual load areas are geographical subdivisions which for natural, economic, political, or other reasons are served conveniently from a given point of supply. The bulk power system is the combination of receiving stations, transmission lines, and generating stations used to supply bulk power to the load areas. That is to say, the bulk power system is the modern interconnected substitute for the uneconomical and outmoded isolated generating station.

Within any individual load area the process of the delivery of electric energy embraces the process of subtransmission as well as that of distribution. In most cases both of these are necessary. How much of the process of delivery should be assigned to each is a matter of economic determination, and hence may vary greatly with the state of development of the art. The purpose of this paper is to point out some of the fundamental economic factors involved in the design of load-area delivery systems as affected by recent advances in the art.

The following nomenclature will be used:

1. A "load area" is a geographical area, usually determined for natural or economic reasons, that is supplied with electric power as a unit and in general mainly from a single receiving point or station.

2. The "bulk power system" is the combination of receiving stations, transmission lines, and generating stations used to supply energy in bulk or wholesale quantities to load areas.

3. "Generation" means energy production plant and process to and including the generator voltage bus or equivalent point.

4. "Transmission" will include step-up transformation at generating stations and transmission lines thence to load area receiving stations.

5. A "receiving station" will indicate a station receiving energy for delivery throughout a load area. Since it replaces a generating station it is a part of the bulk power system.

6. "Delivery" will mean the entire plant and process involved in the transportation of energy from a receiving station to consumers within a load area.

7. "Subtransmission" will mean the plant and process involved in the transportation of energy from a receiving station to distribution substations within a load area. It is thus a subdivision of delivery.

8. A "substation" will mean a station receiving energy from a subtransmission system and delivering it to a distribution system. The substations are a part of the delivery system.

9. "Distribution" will mean the plant and process involved in the transportation of energy from the distribution substations to the consumers within a load area. It is also a subdivision of delivery.

10. "Installed capacity" of a station or group of stations is the sum of the rated capacities of all units installed therein of the kind of equipment that performs the major function of the station or group.

11. "Spare capacity" is the rated capacity of equipment installed in anticipation of breakdown or other service interruption of units of equipment.

12. "Firm rating" is the maximum load that the station is designed to carry with the spare capacity out of commission.

13. "Firm-rating factor" is the ratio of firm rating to installed capacity.

Methods used to provide electric service in any particular load area depend on the size of the area, the character and density of the load, and the available sources of power. An area to be served from a nearby generating station might be treated quite differently from an area to be served from high voltage transmission lines with one or more receiving stations delivering power to the subtransmission system within the area. The presence of a nearby generating station may be a large factor in determining the voltage and arrangement of the subtransmission system, and may affect the choice of voltage and the number of receiving stations or main distributing centers; whereas, in a territory served from high voltage transmission lines, there may be greater freedom in the choice of the subtransmission voltage and the number and location of receiving stations.

The problem considered in this paper is that of a typical large urban load area served from a nearby generating station. It is the intent to show the effect of various factors in the determination of a proper balance between transmission, subtransmission, substations, distribution feeders, etc., that will result in minimum over-all cost consistent with satisfactory reliability, efficiency, flexibility, voltage regulation, etc.

The principal elements of the problem are the determination of the voltage and arrangement of the subtransmission system, the size, type, and system of connection of substations and the capacity, length, voltage, and arrangement of distribution feeders. The secondary mains and service laterals will not be considered in this paper. With this exception, the entire problem of "delivery" within the load area will be considered as a whole, assign-

ing to each element such place, magnitude, and function as to give the best over-all results in the light of fundamental principles, and fully recognizing the opportunities offered by recent advances in the art.

Fundamental Principles

Some of the fundamental principles affecting the design of any load area delivery system are as follows:

1. The choice of the voltage for transmitting electric power depends not only on the distance, but also on the amount of power to be transmitted.

2. A proper economic balance should be established between subtransmission lines, substations, distribution feeders, etc., for the best over-all results.

3. The "firm-rating factor," or the ratio of "firm rating" to total installed capacity, is one of the most important factors in the over-all cost of any load area delivery system.

In applying these fundamental principles advantage should be taken of recent advances in the art which have a decided effect on the problem of load area delivery system design. The most important of these recent developments are (1) automatic substation equipment, and (2) unit type of construction.

Choice of Voltage

Choice of the voltage for transmitting electric power depends not only on the distance, but also on the amount of power to be transmitted. The effect of the amount of power often is overlooked though, as a matter of fact, it really affects the choice of voltage to an even greater extent than the distance. For instance, the proper voltage for transmitting a large block of power a distance of 100 miles probably would be at least 100 kv though the proper voltage for smaller amounts of power probably would be considerably less. An extreme case of this is found in modern telephone systems where very small amounts of power are transmitted 100 miles or more at voltages of the order of 100 volts.

The problem of determining the proper voltage for transmission often is encountered when a generating station is located on the outskirts of a city, and a choice must be made between high voltage transmission lines around the city to one or more main distributing centers on the opposite side for supplying some of the substations as compared with underground transmission direct from the generating station to all of the distribution substations at the voltage of the generating station bus. In many cases the over-all cost of the system would be higher with high voltage lines around the city than with underground transmission direct from the generating station, unless the amount of power to be transmitted to the opposite side of the city is quite large. In any case the reliability of service would be greater with a comparatively large number of underground circuits than with a smaller number of overhead lines.

This particular problem was encountered in Buffalo, N. Y., in connection with the building of the new 60-cycle delivery system. Experience in the development of the older 25-cycle system had led to the adoption of 22 kv for underground subtransmission in Buffalo as long ago as about 1920. The principal source of power for the 25-cycle system was the 66-kv transmission lines from Niagara Falls. These lines served 2 main receiving stations on opposite sides of the city. The C. R. Huntley Steam Plant operated principally as a stand-by station and was connected into the system at one of the 2 main receiving stations.

In the 60-cycle system, however, it was evident that the principal source of power would be the new C. R. Huntley Steam Plant No. 2 which was to be located about 8 miles from the center of gravity of the load. It is about 4 miles from the generating station to the nearest substation and about 16 miles to the farthest substation. The shortest available route for a high voltage transmission line to a receiving station on the opposite side of the city is about 20 miles. The total load involved is a little more than 100,000 kw. Studies indicated that the over-all cost of the system would be less with 22-kv underground transmission direct from the generating station to all of the distribution substations than with part of the substations supplied from the generating station and the rest supplied from a receiving station on the opposite side of the city with the necessary high voltage transmission lines, step-up and step-down transformers, and switching equipment.

Any of 3 conditions may change this situation in the future so that a high voltage system probably would be justified if: (1) the amount of power that could be distributed from the opposite side of the city increased to an amount of the order of 100,000 kw or more; if (2) a major source of power should be made available from elsewhere at high voltage in the future, because then it would be necessary to provide step-down transformers somewhere and their location would not greatly affect the cost; or if (3) continued growth should result in congestion of ducts and cables or excessive concentration of capacity at and near the generating station. This problem would be quite different if the subtransmission voltage were lower, and it might be affected by other local conditions. Each case therefore should be considered on its merits before arriving at a decision.

Balance Between Subtransmission and Distribution

A proper economic balance should be established among subtransmission lines, substations, distribution feeders, etc., for the best over-all results in any load area delivery system. Obviously, the subtransmission circuits should reach as near to the load as practicable in order to take full advantage of the subtransmission voltage before stepping it down. However, it would be a fallacy to extend these circuits to such a point that their additional cost would exceed the saving in distribution circuits.

The determination of this balance between subtransmission and distribution circuits is influenced greatly by the size and spacing of substations as well as by the difference in voltage. It is one of the most important of the problems involved in delivery system design. The best over-all results in any delivery system will be obtained with a proper balance between subtransmission lines, substations, distribution feeders, etc.

Firm-Rating Factor

The firm-rating factor, or the ratio of firm rating to total installed capacity, is another highly important factor in the over-all cost of any distribution system. While the cost per unit of capacity of most electrical equipment varies inversely with the size of the unit, the use of small units nevertheless may result in a lower over-all cost on account of the higher firm-rating factor which may be obtained by the use of small units. As an illustration, a substation designed for 6,000 kva with one spare transformer unit may be designed with different numbers and sizes of units resulting in different firm-rating factors as shown in Table I.

Table I—Firm-Rating Factor as Affected by the Number and Size of Individual Units

No. of Units	Size of Units, Kva	Total Installed Capacity, Kva	Firm Rating, Kva (Without Overload)	Firm-Rating Factor, Without Overload	Firm-Rating Factor With 25% Overload
2	6,000	12,000	6,000	0.50	0.625
3	3,000	9,000	6,000	0.66	0.833
4	2,000	8,000	6,000	0.75	0.937
5	1,500	7,500	6,000	0.80	1.000

The over-all cost of such a substation with small units and a high firm-rating factor may be less than the cost with large units and a lower firm-rating factor. The firm-rating factor is equally important in the transmission system or in any part of the system where provision must be made for taking equipment out of service without interruption.

Design of Substations

The distribution substation is undoubtedly the most important element in the distribution system in any load area. Advances in the art have introduced opportunities for revolutionary changes in the design of substations which completely change the entire problem of delivery system design.

In the early days it was necessary to provide continuous manual supervision of all important substations, and the cost of this supervision made it necessary to limit the number of substations. This resulted in rather large substations serving large areas, and required long distribution feeders with considerable inequalities in the lengths of individual feeders. This made it necessary to provide individual voltage regulators on each feeder. The short-circuit current available in these large substations often reached values above the safe limits of the feeder regulators and made it necessary in many cases to provide feeder reactors to protect the regulators.

Probably the most important single development in load area engineering in the present generation was the introduction of automatic substation equipment. It entirely eliminated the need of continuous manual supervision, thus introducing the possibility of splitting up the substations almost without limit. This offered the opportunity of using a much larger number of substations, located much nearer their respective loads, and permitted extending the subtransmission circuits and shortening the distribution feeders. This made possible an entirely different balance between subtransmission and distribution circuits as compared with the balance when manual supervision was required. Naturally there was a considerable time lag before full advantage could be taken of these possibilities, and even now the influence of the old practice still may be recognized. Automatic equipment often has been used in large substations without taking advantage of the opportunity to split up the substations and obtain a more advantageous balance between subtransmission and distribution circuits.

One might naturally assume that the cost per unit of capacity of small substations would be higher than that of large substations, but this is not necessarily the case as the conditions controlling the design of substations change completely with their size and spacing. The use of smaller substations results in closer spacing and in shorter distribution feeders, and consequently less difference in the length of individual feeders. This eliminates the need of individual feeder regulators and permits the use of bus regulators using larger regulator units at a lower cost per unit of capacity. The total regulator capacity required for bus regulators is usually less than for individual feeder regulators on account of diversity between feeders, and this results in further savings. The short-circuit current can be kept low in small substations, and this permits further savings by omitting feeder reactors or by using smaller circuit breakers or both. There is much greater freedom in the choice of locations for small substations as they can be placed on small lots in almost any neighborhood; this may result in a lower total cost for land even though more parcels are required than for a system with large substations. These factors may combine to make the cost per unit of capacity for small substations no greater and in some cases considerably less than that for large substations.

Switching Equipment Vs. More Transformers or Circuits

While a certain amount of switching equipment always is necessary, and while additional switching equipment sometimes will increase the usefulness of transmission circuits, transformers, or other equipment, in many cases the cost of additional switching equipment would be higher than the cost of additional circuits or other equipment that would

accomplish even more than the additional switching equipment. For instance, the cost of a single 22-kv oil circuit breaker of reasonable interrupting capacity with the necessary structure and accessories may equal or exceed the cost of 10,000 kva of substation transformer capacity, or 2 miles of underground cable. The space occupied by switching equipment also may be an important factor in determining how much of this equipment should be used.

In the early days it was common practice to provide high voltage switching equipment for each incoming line and for each transformer bank. The first important change in this practice consisted of connecting each subtransmission circuit directly to one substation transformer of about the same capacity and omitting the high voltage bus and switching equipment. The next important change in this practice consisted of connecting each subtransmission circuit to several transformers in different locations. This practice has become quite common in low voltage a-c networks, but the same scheme can be used to good advantage in serving distribution substations and, so applied, permits taking advantage of the economy of large transmission circuits, small distribution substations, and small units in each substation, all at the same time. (See Fig. 1.)

Another important factor in the design of substations is the use of smaller units than commonly have been used in the past. The principal advantage of the use of small units is the opportunity to obtain a high firm-rating factor by using more units in each substation. Small units also present an opportunity to take maximum advantage of standardization and unit type of construction, and permit the installation of additional capacity in small increments when and where it is required.

Another very important factor affecting the cost of substations is the physical arrangement of the equipment in the substation. Appreciable savings can be made by so arranging the equipment that a minimum of aisle space is required. Switching structures can be designed to require an operating aisle on only one side, and this alone permits appreciable savings particularly if the other equipment in the substation is so placed as to take advantage of the same aisle. (See Fig. 3.)

There are 2 other important advances in the art which affect the problem of distribution substation design. The more general use of self-cooled transformers, resulting from improvements in transformer design and construction, offers greater freedom in the determination of the size and spacing of substations by the elimination of water cooling. The introduction of metal enclosed bus and switching structures greatly facilitates standardization and unit type of construction.

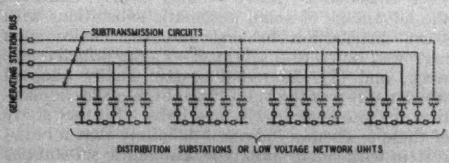

Fig. 1. Diagram of typical group of subtransmission circuits in Buffalo

Each subtransmission circuit serves several units in different locations permitting the use of large circuits even with small substations and small substation units

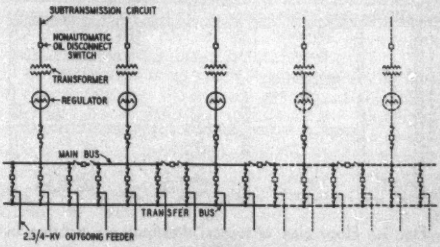

Fig. 2. Diagram of typical distribution substation in Buffalo

Units paralleled on the low voltage side only with no high voltage bus or automatic high voltage switching

The use of small automatic substations with small units and with a minimum amount of switching equipment probably offers greater opportunities for savings than any other element in the design of load area delivery systems.

Small Unit Type Substations at Niagara Falls

One of the first applications of small, unit type of substation construction to a general distribution system was made at Niagara Falls starting in 1925. This was not a complete revamping of the system, but involved only rather minor additions to the existing system to take care of the growth of the load. In this case the subtransmission voltage is 12 kv and each subtransmission circuit serves 2 2,000-kva units in 2 different substations. The initial installation consisted of 4 units, 2 of which were installed as single unit substations with reserve connections from the old 2.3-kv distribution system. Additional units have been installed as required by the growth of the load until at present there are 13 units installed at 5 different substations. Some of these substations still depend on the old 2.3-kv distribution system for reserve connections, but others are entirely independent of the old system. The old system is still in service and will continue in service to the limit of its capacity without any undesirable effect on the newer parts of the system.

New System in Buffalo

An outstanding example of what can be accomplished by the use of small substations with small standardized units is the new 60-cycle load area delivery system in Buffalo, a description of which

has been published. (See "100,000-Kw Distribution System as a Single Project," *Electrical World*, July 25, 1931.) In this system the subtransmission voltage is 22 kv and each subtransmission circuit serves 4 2,500-kva units in 4 different substations. The subtransmission circuits are all underground because of city ordinances. There is a total of 26

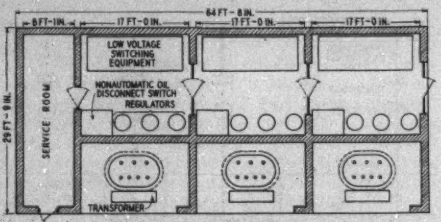

Fig. 3. Floor plan of typical distribution substation in Buffalo

Placing the equipment along a single aisle permits compact arrangement without sacrificing accessibility or safety

substantially identical substations each serving a territory of about one square mile (except in the outlying sections). The initial installation at each substation consists of 3 2,500-kva units served from 3 different subtransmission circuits, and paralleled on the low voltage side only. There is no high voltage bus or switching equipment except a nonautomatic oil disconnecting switch for each transformer. Provision is made for at least 5 units at each substation location. The transformers are located in compartments accessible from the outside of the building and may be enclosed readily in locations where noise is a factor. (See illustrations.)

The low voltage switching equipment consists of a main bus and a transfer bus with one oil circuit breaker for each transformer circuit and each feeder, and with bus section breakers in the main bus between units. Bus regulation is provided by a bank of induction regulators in the low voltage circuit of each transformer bank. A simple wattless compensator scheme insures stability between regulators and permits compensation for line drop even though the regulators are paralleled on the load side.

All switching is done in the 4-kv circuits. The transformer circuits are equipped with overcurrent and reverse power relays, thus providing full automatic protection to isolate faults in subtransmission circuits, substation transformers, or regulators, without any interruption to service. With this scheme, low voltage a-c network units may be and are supplied from the same transmission circuits as substation units. This permits spreading the supply to the low voltage a-c network over a large number of different subtransmission circuits and taking advantage of the diversity between substation and network loads in the subtransmission circuits.

Careful attention was given to the physical arrangement with the result that, while all of the equipment is readily accessible, these substations occupy an area of only about 0.25 sq ft per kva of installed capacity including the transformer compartments. This was accomplished by designing the low voltage switching structure in such a way that it requires an operating aisle on only one side, and by providing a single central aisle running the full length of the substation with the low voltage switching structures along one side and the regulators and high voltage oil disconnects along the other. By this arrangement a minimum of space is occupied without sacrificing accessibility or safety, for there are at least 2 ways out from any place in the substation where men have occasion to work (see Fig. 3).

Distribution feeders are comparatively small, and the only additional equipment required for additional feeders is the feeder breakers which are small because of the low short-circuit capacity of the small substations. The distribution feeders are so short that there is no need of carrying the main feeder to the load center and providing radial branches from there. Instead, the load is picked up along the main feeder without any duplication between the feeder main and branches. With the small short distribution feeders, each feeder has a limited exposure and the number of customers affected by an outage is comparatively small.

While this is probably the largest load area delivery system ever built at one time as a single project, the striking economies realized in this system were not the result of the unusual conditions incident to the construction of an entire system at one time, but were due almost entirely to the careful application of the fundamental principles expressed in this paper. The substations are small, simple, unit type substations providing a high degree of reliability of service with a minimum of switching equipment. The firm-rating factor is high for both substations and subtransmission circuits, and there is a proper balance between subtransmission and distribution circuits.

Comparison of Primary Network and Radial System Used in Buffalo

Before the new system in Buffalo was built, careful consideration was given to the choice of the type of system to be used. For the principal business district, the low voltage a-c network was adopted. For the rest of the territory, several different schemes were considered. Early studies clearly indicated the advantage of small automatic substations with short distribution feeders, and the choice soon narrowed down to 2 schemes: (1) the primary network, and (2) the radial system finally adopted which really was the outgrowth of the earlier application of these ideas at Niagara Falls. Further study of these 2 schemes indicated definitely that a radial system with small, unit type, automatic substations would be at least the equal of the primary network in reliability, efficiency, and operating characeristics, and would be more flexible and would cost considerably less than a primary network with equivalent firm rating.

Two particular difficulties in the primary network scheme were brought out in the studies. One is that the irregularities in the system caused by parks, waterways, railroads, etc., affect the firm-rating factor to a much greater extent in a primary network than in a system with separate substations. The other difficulty is that, even in a uniform network, the load will not divide uniformly among the transformers in service under all conditions of operation on account of the impedance in the network. The effect of this is 2-fold: It requires more transformer capacity than might be expected in a network, to avoid excessive load on any unit when some units are out of service; and it dictates the location where transformers must be installed, as load cannot be forced at will from one location to another in a network. This difficulty is encountered both in the initial installation and in providing for growth of the load, which means that units must be placed, or added, at or near the loads they are intended to carry.

In the Buffalo radial system the load on each substation always will divide uniformly among the transformers in service; the division of load between substations can be controlled definitely, and load may be shifted and forced from one substation to another from time to time at will, by simply cutting and rearranging the distribution feeders. Ordinarily this would consist of transferring sections of distribution feeders from one feeder to another in the areas where the feeders from one substation meet those from another substation. In such a system, where the substations are comparatively close together, the flexibility in this respect is almost unbelievable.

Recognition of these factors in the studies indicated that the total transformer capacity required for a primary network would be as great, or even greater than that required for the Buffalo radial system. The studies indicated that the total mileage of subtransmission circuits required for a primary network would be considerably greater than for the Buffalo radial system because of the scattered locations of substations and the need of interleaving in the network. Some additional subtransmission mileage might be justified if a saving could be made in distribution circuits, but these studies indicated practically no difference in the total mileage of distribution circuits in the 2 systems. This apparently is due to the fact that, while there would be about the same total number of feeders, each feeder in the Buffalo radial system runs from its substation to its load and stops; whereas, in the primary network each feeder must continue beyond its load to the adjacent substation, and these continuations often involve crossing areas where there is no other need for distribution circuits.

These studies indicate also that the total cost of substations would be considerably higher in the primary network because the primary network unit substations are so small that the cost per unit of capacity would be considerably higher than for the substations used in Buffalo. In addition to this, nearly twice as much switching equipment would be required in a primary network as in the Buffalo radial system because in a network there must be a circuit breaker at each end of each feeder, whereas, only one circuit breaker is required for each feeder in the Buffalo system with about the same total number of feeders.

The fact that the cost of subtransmission circuits and substations would be considerably higher for a primary network than for the Buffalo radial system, without a corresponding saving in distribution circuits, indicates that the primary network scheme involves extending the subtransmission circuits beyond the economic balance point.

As to the operating characteristics, there is little to choose between the 2 systems so far as reliability, efficiency, and voltage regulation are concerned. The only interruptions to be feared in either system are those caused by faults on the distribution circuits themselves, and such faults will cause interruptions to all of the service connected directly to the faulty circuit in either system. Since there would be about the same total number of feeders in both systems, there would be about the same amount of load on each feeder, and the number of customers affected by an outage on a distribution circuit would be about the same in either system. Loop feeders would offer some protection, but complete protection against such faults would require multiple supplies at service voltage from different distribution feeders in either system.

The Buffalo system has a decided advantage over a primary network in flexibility on account of the facts that the division of load can be controlled definitely, and that load can be shifted and forced from one location to another at will. This means that if load growth appears near a substation that is fully loaded and spare capacity is available in a nearby substation, the installation of additional capacity at the fully loaded substation often may be avoided by simply cutting and rearranging distribution feeders to shift load to the substation having spare capacity available. It also means that if

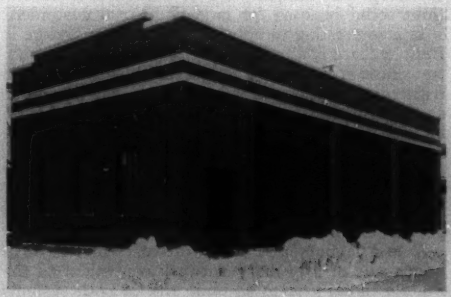

Fig. 4. Exterior of typical distribution substation in Buffalo

Small substations may be located on small lots in almost any neighborhood. Transformers are accessible from the outside and may be enclosed where noise is a factor

load growth appears along a group of fully loaded subtransmission circuits and spare capacity is available in a nearby group, the installation of additional subtransmission circuits often may be avoided by shifting load to the lightly loaded subtransmission circuits. In a primary network there would be practically no choice except to install additional capacity at or near the load, even though spare capacity might be available elsewhere in the network. The Buffalo radial system also would have the advantage should uniform growth of load appear over the entire area; in that case a minimum of additional subtransmission and substation capacity could be installed and made available to the entire area by shifting load to the new units, whereas, in a primary network it would be necessary to install additional capacity throughout the network. This advantage is particularly noticeable and significant in a large area.

The Buffalo radial system also has remarkable flexibility in serving industrial loads. The distribution feeders are so short that there is very little voltage drop in the feeders themselves, and the voltage regulation at the substation bus requires only a very slightly rising characteristic. This means that small industrial customers may be served from the same distribution feeders as lighting customers. Industrial customers of moderate capacity, even up to several thousand kilowatts, may be served from any of the substation busses by means of separate 4-kv feeders. Larger industrial customers may be served directly from the 22-kv subtransmission circuits in which case high voltage switching equipment could be installed in the customer's plant; or preferably, an installation similar to the power company's own distribution substations could be used for large industrial customers.

It is interesting to note that in the new system in Buffalo there is already one group of 3 22-kv subtransmission circuits that serves 2 substations in residential districts, 1 substation in the wholesale and warehouse district, 1 substation serving a large industrial customer, and several low voltage a-c network units in the principal business district. As the system develops, advantage will be taken of such opportunities to benefit by the diversity between the various types of load, to the maximum possible extent.

Actual layouts and comparative estimates have been made of a primary network equivalent to the Buffalo radial system as built and of both systems extended to double the firm rating. These estimates indicate that the comparative cost of the 2 systems would be about as shown in Table II.

These studies indicate the difficulty of making a satisfactory application of the primary network scheme under actual conditions, particularly in a large area. Several trials were required to accomplish a reasonable layout, and even after repeated attempts the initial installation of 130 units has 13 units with only 2 tie feeders and 45 units with only 3 tie feeders, leaving only 72 of the 130 units with 4 tie feeders. In the extension with 217 units there are 19 units with only 2 tie feeders and 84 units with only 3 tie feeders, leaving only 114 of the 217 units with the 4 tie feeders. Even these layouts include a number of "impossibilities" such as tie feeders crossing Delaware Park, substation units in the midst of the very finest residential sections, and several things that simply could not be done at all in an actual installation.

Conclusions

To review briefly, modern load area delivery systems must provide a high degree of reliability, efficiency, flexibility, voltage regulation, etc., with the maximum over-all economy. Reliability requires multiple subtransmission circuits to each substation, multiple units in each substation, and small short distribution feeders. Economy requires a proper economic balance between the various elements of the system. It requires also that maximum use be made of existing equipment before additions are made, and that when additional capacity is required it be installed in small increments.

The radial system, if designed in accordance with the principles outlined in this paper, meets these requirements very effectively. It takes advantage of the economy of large subtransmission circuits; at the same time, by serving several substation units from each subtransmission circuit, it permits the use of small, simple, multiple unit substations and short distribution feeders. It provides high grade service and takes maximum advantage of diversity between domestic, commercial, and industrial loads. The radial system permits shifting of load to allow maximum use of existing facilities before additions are made. It permits the installation of additional capacity in small increments when required and offers considerable freedom in the location of such additional capacity. It is an economical system either as a supplement to an existing radial system or as a complete system covering an entire area. In either case it may be installed in small increments as required by the growth of the load. In short, the radial system provides maximum flexibility and efficiency of use of equipment and is at least equal to any other system, except the low voltage a-c network, in reliability, efficiency, voltage regulation, and other operating characteristics.

Table II—Comparative Capital Costs of Buffalo Radial System and an Equivalent Primary Network

	Initial Installation			
	Buffalo Radial System		Equivalent Primary Network	
Subtransmission	243 miles	100%	346 miles	142%
Substations	26 7,500-kva substations	100%	130 1,500-kva units	171%
Distribution feeders		100%		100%
Total		100%		136%
	Double Initial Firm Rating			
	Buffalo Radial System		Equivalent Primary Network	
Subtransmission	407 miles	100%	570 miles	131%
Substations	26 12,500-kva substations	100%	217 1,500-kva units	182%
Distribution feeders		100%		100%
Total		100%		135%

The 3-Phase Electric Arc Furnace

The 3-phase electric arc furnace has established itself definitely as an important industrial unit in the production of ferrous materials. With the efficiency of the arc furnace being increased, and with the overall cost of installation and operation now being comparable with that of an equivalent open hearth, an even more extensive application is indicated for the future. This paper discusses in a general way the classification, rating, and methods of operation of 3-phase arc furnaces, outlines some of the modern developments in design, and points out the relative advantages of these units in specific applications.

By
SAMUEL ARNOLD, 3rd
NONMEMBER
Engr. & Sales Representative, Heroult Electric Furnaces, Pittsburgh, Pa.

A QUARTER OF A CENTURY of progress in steel making has firmly entrenched the 3-phase arc furnace as an industrial unit. In the entire field of ferrous metal production, the 3-phase arc furnace has been developed to the point where it would be difficult if not impossible to produce certain grades of material without its assistance, and many advances in the art of utilizing ferrous materials could not have been possible.

In the past few years in particular, large arc furnaces have been employed with excellent results. One of the problems of the use of large furnaces is the introduction of power into the furnace, and in particular the utilization of the energy without unnecessarily superheating the bath at certain points. The maximum rate at which energy can be introduced into a molten bath without detrimental effect as yet is undetermined, but it is known definitely that there are certain limits.

Efficiencies of arc furnaces, and in particular of large units, have been increased materially by the use of higher energy inputs; however, the problem of high power demand charge has made it necessary to consider efficiency increases along other lines, such as insulation. As yet little has been done with the insulation of arc furnaces, but the successful insulating of open-hearth units has indicated possibilities.

Advantages accruing from the application of arc furnaces are not to be considered from a cost standpoint only, but increased flexibility and metallurgical control obtainable with the use of the 3-phase arc furnace has been largely responsible for its continued application. In large units, the costs of installation and operation, all things considered, are now somewhat comparable to open-hearth costs; with this in mind, the possibilities of increased use for the 3-phase arc furnace are better than ever before.

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Classification

For general classification, 3-phase arc furnaces can be divided into 3 types: furnaces used only as melting units, furnaces used for both melting and refining, and furnaces used for refining only. Under this general classification the arc furnace can be subdivided depending upon the quality and type of product desired, the material available for conversion, and the metallurgical results to be obtained. While in nearly all arc furnaces used for melting some refining is done incidental to the operation, the term "melting" unit is given to a furnace in which conversion of material primarily necessitates melting. The term "melting and refining" unit generally is given to an arc furnace in which it is necessary not only to melt the charge, but also to effect some metallurgical change and produce a material different in chemical and metallurgical qualities from the initial charge. By a "refining" furnace usually is meant one in which hot metal is charged either from an open hearth, bessemer vessel, or a cupola, and the hot metal changed chemically or metallurgically to produce a product different from the initial charge. Obviously, there is considerable overlapping in these classifications.

Arc furnaces are classified also with relation to the product, and here 2 general terms can be applied, namely: arc furnaces for the production of ingots, and arc furnaces for the production of castings. In general in the production of steel ingots, the furnace is supplied with a basic or magnesite bottom, and is termed a "basic" unit, while most of the furnaces used for the production of castings have bottoms of acid material or silica, and are called "acid" units. There are, of course, a few applications of acid furnaces for the production of ingots and, conversely, quite a number of basic furnaces used in the production of castings.

Of the ferrous materials produced in arc furnaces, the application is generally for carbon and alloy steel ingots, carbon and alloy steel castings, gray iron, and malleable castings. As a rule furnaces for producing castings are of the smaller sizes, varying from 500 lb to 10 tons in capacity. Ingot making furnaces are usually from 3 to 100 tons in capacity, although some relatively small ingot producing furnaces are used in the tool steel field.

Furnaces for producing metal for both ingots and castings can be operated as batch type units with cold charge, batch type units with hot charge, or semi-continuous melting units with either hot or cold

A 100-ton 20,000-kva 6-electrode Heroult electric melting furnace; batch charge with cold scrap for ingot production

charge. In batch type operation the charge is placed in the furnace, melted and/or refined, and then tapped by means of tilting the unit. In semicontinuous operation a full charge, either hot or cold, is placed in the furnace, melted and/or refined, and then a portion of the metal is tapped at intervals at which times charges of approximately the same tonnage are added. In semicontinuous work the furnace is drained at intervals, depending upon the cycle of operation, and usually the quantity of the charge is reduced so that at the proper time the last tap will completely drain the furnace. In the past, and particularly during the World War, some ingot producing furnaces were operated with charges of hot metal. However, in nearly every operation today where carbon or alloy ingots are produced in arc furnaces, the batch type of cold melt is employed; and there is at least one furnace in which the semicontinuous melting process is utilized, charging cold scrap. In casting work where carbon or alloy steel castings are produced, the usual practice is to batch-melt, while in the iron and malleable fields there is a tendency toward semicontinuous operation with either hot or cold charges.

Rating and Capacity

A great deal of confusion in the capacity rating of furnaces has been caused by nonuniform ratings. In the early development of 3-phase arc furnaces, a nominal tonnage rating was given the units which was based upon the holding capacity with a molten bath and a theoretical contour of bottom, allowing a certain volume for slag. In nearly every case it was found that by slightly changing the shape of the bottom, additional tonnage could be placed in the furnace, and with the introduction of higher power inputs the furnaces were overloaded. Later a tons-per-hour rating was given furnaces, which was explicit only when associated directly with the particular product to be made. Sometimes the size of the shell and the transformer capacity were given, but these did not tell the operator what tonnage might be expected. Nominal ratings still are given, usually arbitrary ratings based upon the size of the shell.

A description of the various methods of operating 3-phase arc furnaces may illustrate to better advantage what is involved in establishing capacity ratings. For batch type melting in the casting industry, assume a furnace rated at 3 tons nominal capacity. The furnace is lined with an acid bottom composed of gannister or silica sand and the side walls and roof are of silica brick. The transformer capacity is approximately 2,500 kva with taps of various voltages available at the will of the operator. A charge of approximately 6 net tons is placed in the furnace either through the door by means of hand charging or chute charging, or through the roof which can be removed for this purpose. The transformer switch is closed and some intermediate voltage applied that has been found most desirable for the type of charge utilized. The electrodes are started down and the load put on the furnace. This intermediate voltage usually is maintained from 10 to 20 min. until the electrodes have bored a hole through the scrap and the arc is more or less under cover. At this time the transformer taps are changed and full load is thrown on the furnace at a higher voltage until the charge is nearly melted. Usually at this period both the voltage and the load are reduced and after complete melt, the furnace operator takes samples of the steel for analysis. If ordinary steel castings are being produced, the melter by breaking a sample and reading the fracture can tell, approximately the carbon content of the bath, although present practice usually augments this by laboratory analysis. When reports have been received from the laboratory, the melter makes the necessary additions; and after the metal has reached the proper metallurgical condition and temperature, the tap is made. For ordinary steel castings this usually takes about 2 hours, so the furnace may be said to have a nominal rating of 3 tons per hour.

If alloy castings are being produced, and particularly alloys requiring basic treatment, the furnace, of course, is operated with a basic bottom. In most cases the first slag produced after melting is raked off, as this slag is usually of an oxidizing nature; and as it is slagged off, the impurities such as phosphorous contained in the slag are removed. A second slag then is made, and in rare cases 3 or 4 slags are necessary. In basic furnaces the time usually required for refining is much longer, as the metallurgical results desired are entirely different. For this reason furnaces with basic bottoms require a longer period of time for making the heat and usually are not rated on a tons-per-hour basis.

As an example of batch type refining or batch type superheating with hot metal, assume a 15-ton unit containing about 20 tons of hot iron. This unit would be acid lined, and the charge made from a ladle through the rear door. The metal would have a temperature of approximately 2700 deg F when received into the furnace and must be superheated to 2,950 deg F. This is accomplished by applying about 5,000 kw at a comparatively low voltage, the time required being from 15 to 20 min. While some slag is formed, if from no other source than from the drippings of the side walls of the unit, very little attention is given to metallurgical changes except in the results obtained by superheating; and as soon as the proper temperature is obtained, the furnace is tapped. In this case 3 taps will be made per hour or 60 tons removed from a 15-ton unit in an hour; the furnace thus would have a rating of 4 times its nominal capacity in tons per hour.

Again, assume a furnace rated at 25 tons and used for producing alloy steel ingots; this furnace, depending of course upon the size of the scrap, would be charged with some 30 to 35 gross tons by means of an open-hearth charging machine. The melt would be made in the usual way, and after melting down, the first slag would be removed as previously mentioned. Careful laboratory analysis would be made of samples taken from the furnace and additions made to produce the grade of steel desired. Careful working of the furnace slags would be in order; and after the melter was satisfied as to temperature and metallurgical conditions, the heat would be tapped. Usually from $4^1/_2$ to 5 heats would be produced in 24 hr, and so the tons-per-hour rating of a furnace of this sort would depend entirely upon the type of product.

The foregoing examples serve to show that the tonnage rating of a furnace depends entirely upon the final product and the type of charge used. Usually in the casting industry a ton is spoken of as 2,000 lb of metal, and in the ingot industry 2,240 lb of metal. Some furnaces are rated on a tons-per-hour basis, some on a nominal holding capacity basis, and some are rated as to size of shell and transformer capacity; for each size of shell and a given transformer capacity a tons-per-hour rating can be determined for the product desired. As to furnace ratings, therefore, the size of the shell, the transformer capacity, and the nominal holding capacity should be given, as well as the approximate tons-per-hour rating for a definite specified product.

Modern Developments

Great progress has been made during the past 25 years in the mechanical features of arc furnaces. Designs have been made coördinating workability with efficiency of operation; and such parts as water cooled door frames, arches and doors, electrode holders, electrode cooling glands or roof coolers, and other important parts have been much improved and simplified in design. In addition, methods of carrying heavy currents over the furnace by the use of water cooled copper tubing to minimize hysteresis and eddy current losses, the design of the mast structure to permit various changes of electrode circles for different operating characteristics, and such mechanical features as ball and roller bearings in the moving parts, all have tended to make for efficiency and improved operating characteristics. On the surface there is seemingly little chance for material improvement of design along mechanical lines, except perhaps in the methods of charging; but unquestionably improvements will be made as the use of electric furnaces increases and new problems arise.

Electrical equipment, of course, has kept pace with other developments. With improvements in regulators and transformer design, and a knowledge of the proper values of reactance for given conditions, the method of introducing energy into the furnace has been changed materially. In addition to this, modern furnaces usually are equipped with the so-called "multiple voltage control" which provides several voltages available at the will of the operator. On small furnaces, usually 3 voltage taps are provided; but on the larger units 5 or 6 and in one case as many as 12 different voltages are available at the immediate will of the operator, by means of a combination of transformer taps and delta-Y switching accomplished by motor operated tap changers with the control on the operator's panel. This gives the operator a choice of different lengths of arc and allows him to choose the voltage that is most desirable for the different steps of melting and refining.

In the past few years the tendency has been toward larger transformer capacities for quicker melting, hence shortening the radiating period during the melt with consequent higher efficiency. Of late, however, consideration has been given to transformer capacities primarily on account of the usual high power demand charge, and doubtless a great deal of thought is being given to improving the efficiency of arc furnaces by means other than simply forcing power into the furnace as rapidly as possible. There is a limit, of course, to the amount of energy that can be utilized with a certain size of furnace shell, as refractory and metallurgical problems arise when energy is introduced into the furnace at too rapid a rate.

In recent years open-hearth furnaces in some instances have been insulated successfully, and this naturally leads to the thought that 3-phase arc furnaces also can be insulated to increase their efficiencies; while some experiments are being carried out along this line, there have been as yet

no definite results. The major problem of insulating an arc furnace is in limiting the power input so that energy will not be introduced at a rate sufficient to increase the temperature difference between the refractories and the charge. Depending upon the temperature, energy can be dissipated in a ferrous bath at a certain rate; and if power be introduced too rapidly, it, of course, would raise the temperature of the furnace itself to the point where refractory failure would occur. There are other problems in connection with insulating arc furnaces, but they are of a minor nature and no doubt can be overcome.

A 15-ton 5,000-kva 3-electrode Heroult electric melting furnace, semicontinuous hot charge for gray iron castings

The insulation of arc furnaces and the consequent reduction in power input would accomplish 2 things: (1) the demand charge for a given size of unit would be lowered; and (2) the efficiency of the unit would be increased as a result of the reduction in radiation losses. Obviously, if a certain length of time is required to make a certain heat with a given power demand in a furnace that is not insulated, the same heat could be made in the same time with a lower power demand in an insulated furnace. This is because the rate of radiation is relatively high during the refining period as well as during the melting period; and regardless of transformer capacity and rapidity of melt, this loss during the steel making cycle is not changed, as it is a function of the rate of radiation and the time required to accomplish the metallurgical results.

If, therefore, arc furnaces can be insulated successfully, the operating costs can be improved by lowering the amount of energy consumed per ton of metal produced and also by reducing the power demand charge. The over-all cost of production then will depend upon whether the savings in demand charge and energy requirements will offset the apparently increased cost of refractories. The difficulty is in determining the maximum rate at which energy can be introduced into an insulated furnace, and at present the human element involved has made progress rather slow along this line. New refractories are being developed, however, and new insulating materials tried; and there are excellent possibilities of some good results being obtained.

Large Furnaces

Problems arise in connection with 3-phase arc furnaces of nominal ratings of 25 tons and more which, of course, do not occur with the smaller units. These problems deal with the introduction of large amounts of power. In general, the transformer capacity, or power input per hour per ton of rating, is much less than for furnaces of smaller size. As most of the power available is at 60 cycles, difficulties are experienced with the conduction of heavy currents in introducing the power into the furnace at a good power factor, and careful design is necessary. The tendency on first thought, when higher inputs are considered, is to increase the voltage; but in an arc furnace an increase of furnace voltage means a longer arc, and if the arc is too long the energy is not entirely introduced into the charge—rather, a large portion of it is radiated to the side walls and roof of the furnace with consequent high refractory costs. It is necessary, therefore, to keep within certain limits of furnace voltage and this in turn means higher currents with the increased power. Currents of from 30,000 to 40,000 amp per phase have been applied successfully to arc furnaces with reasonable power factors, but it is questionable if these values will be exceeded. It might be said, therefore, that from the electrical standpoint, there is no difficulty in introducing large amounts of energy through 3 electrodes, and at present as much as 12,000 kw have been applied to a 3-electrode 3-phase arc furnace.

In introducing large amounts of energy, however, the point is approached where the steel will not absorb energy rapidly enough from 3 concentrated areas. Some believe that the limit of power input per electrode is approximately 3,000 kw. With higher values the metal tends to become superheated directly under the electrodes, and when the charge is partially melted down, there is a great deal of agitation and "slopping" of the bath. The actual upper limit of power input per electrode as related to energy dissipation in the charge as yet is undetermined; it depends upon several factors, the primary one of which is the maximum rate at which heat can be disseminated through various ferrous materials.

It is for the reasons previously outlined, therefore, that in the larger 3-phase arc furnaces the rate of power input per ton of charge is lower than in smaller units, and this also is the reason for utilizing multiple electrode furnaces or furnaces with 6 or 9 electrodes which unquestionably will be developed to a greater extent in the future. At present the largest furnace that has been built using 3 electrodes is a unit having a shell 18 ft in diameter. This furnace has a holding capacity of from 60 to 75

gross tons and a transformer capacity permitting 10,000 kw input for the period of melt. There is also one furnace in operation at the present time that has an elliptical shell 29 ft by 20 ft. This furnace has 6 electrodes and is capable of introducing 10,000 kw on each set of electrodes, or 20,000 kw total; the furnace has been charged with as much as 135 gross tons.

Application

One does not use a tool unless there is some advantage in so doing. In a great many cases production could be made in other than electric furnaces at less cost, but the product would be inferior. In other cases the electric furnace shows the best cost. Whether the electric furnace should be utilized or not, depends upon a great many factors including power rates, cost of scrap, metallurgical considerations, and type of product. In general, in the small steel foundry, the electric furnace has proved itself to be a most excellent and economical tool. In the iron foundry where superheating is necessary or where a high grade product is demanded, the electric furnace is well adapted. In the ingot producing field for tool steels and for special alloy steels including stainless steels, the 3-phase arc furnace is unquestionably paramount. In the manufacture of ingots and ordinary grades of steel such as bar stock and steels that usually are made in the open hearth, the use of an electric furnace will depend on the cost of electric power as opposed to fuel costs, and the cost of scrap as opposed to the cost of the charge of the open hearth. In all cases, attention should be given to, and a careful analysis made of, relative costs; for while the electric furnace has the disadvantage of a high energy cost, this disadvantage can be overcome largely by the higher yield and higher efficiency of the electric furnace and the higher quality product that very often is obtained at no additional over-all cost.

During the past few depression years the flexibility of the electric furnace has been brought to the fore, and where this tool has been used it has been recognized unequivocally as having many desirable operating characteristics. As is often the case there have been applications of the arc furnace where such were not warranted, but the resultant failure of the arc furnace to measure up to expectations in these few instances has served only to emphasize the desirability of its use in other fields. The development of the arc furnace in the future undoubtedly will be along the line of large units, as the cost of operation of these units, with the exception of energy, is quite comparable to open hearths of like rating; and as power is produced and sold more cheaply, the large electric furnace will take its place as a close competitor of the open hearth. The use of alloy steels is on the increase, and the arc furnace so far has shown itself to be the most desirable tool for producing alloy steels. In the casting industry, the development of high test irons and the ease with which these irons may be superheated in a 3-phase arc furnace will result in an increased growth in the use of the arc furnace. In the steel casting industry, while at present the arc furnace is used almost exclusively as a smaller melting unit, unquestionably the use of larger arc furnaces will follow the inevitable adjustment between present fuel and power costs.

As an example of what now is being accomplished, it has been demonstrated definitely that with the exception of energy, a large arc furnace can show production costs equal or nearly equal to the production costs obtained in a similar open-hearth where scrap and cold pig are used. The electric furnace is more efficient as to melting loss and, therefore, has a higher yield, and the investment cost of a large electric furnace is not greater but usually less than the cost of a similar open-hearth installation. By similar furnaces is meant, of course, furnaces capable of producing the same number of tons per month. As to energy costs, however, the electric furnace is the more expensive unit to operate. Assuming $1 per ton for open-hearth fuel costs, on the same basis the electric furnace with energy at 6 mills per kwhr would show about $4.50 per ton for power and electrodes. This differential of about $3.50 per ton often can be more than offset by low investment in plant and auxiliaries, in increased metal yield, and in increased yield in the use of alloys. In addition to this, the resultant higher quality product is usually more salable and in most cases commands a higher price.

It is difficult, of course, to visualize the future of arc furnaces; but the rapid recognition of these units, and the part they have played in the development of ferrous materials in the past few years, would indicate an even more extensive application in the future. It seems entirely logical to predict that during the next inevitable cycle of prosperity, the arc furnace will play an increasingly important part in the ferrous industry.

A 50-ton 10,000-kva 3-electrode Heroult electric melting furnace, semicontinuous charge cold scrap for ingot production

Electrodes—Carbon and Graphite

Carbon and graphite electrodes play an important part in many industries; the number of uses of these electrodes is increasing year by year, and the field of application is widening. In spite of these facts, however, published information regarding them appears to be quite meager. In this paper the history of carbon and graphite electrodes is outlined briefly, and the methods of manufacture and industrial applications are described.

By
FRANK J. VOSBURGH
NONMEMBER

National Carbon Co., Inc., New York, N. Y.

THOUGH carbon and graphite electrodes play an exceedingly important part in several industries, notably in the production of abrasives, aluminum, iron, steel, alloys, and carbide in the electric furnace, as well as in the electrolytic production of chlorine, caustic soda, and other substances, the information regarding them is unusually meager. Undoubtedly, this is due primarily to the fact that such electrodes in general have a simple structure and a wholly uninteresting appearance, giving no indication of the difficulties encountered in bringing them to their present state of carefully manufactured articles.

Materials used for manufacturing carbon and graphite electrodes are chiefly anthracite coal, petroleum coke, and hard and soft pitch. The electrodes may be extruded through dies or molded under pressure, after which they are given special baking and cooling treatments. About 2 months are required for manufacturing carbon electrodes, and 3 months for graphite. They can be made in practically any shape and size up to a maximum of 40 in. in diameter for carbon, and 18 in. for graphite.

Graphite electrodes usually are preferred for electrolytic operations, while in electrothermic work both are used depending upon the nature of the process and the result desired. Where either type of electrode may be used, the choice naturally depends primarily upon the over-all cost. Although graphite electrodes cost more than carbon electrodes of the same physical size, the electrical resistivity of graphite electrodes is lower than that of carbon, and hence graphite electrodes are much smaller than equivalent carbon electrodes. The electrode consumption per ton of product varies widely, depending, of course, on the nature of the process and the relative size of the equipment, as well as on the ability of the operator.

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Historical Facts

Historically, electrodes are dated as of 1800 when Sir Humphrey Davy produced the first electric arc using a voltaic pile as the source of current. Davy made the first electrodes by a process not so dissimilar from that now in effect. He took powdered wood charcoal as the carbon and syrup of tar as the binder, mixed them, and compressed the mass to form electrodes for his experiment. Today the process is the same except that coal and coke replace the charcoal, and tar and pitch replace the syrup of tar; molding under pressure still is used, though most electrodes now are extruded under pressure. The final product of today is baked, while Davy does not seem to have carried out that operation.

Little advance was made in the manufacture of electrodes until after the invention of the dynamo in 1867 when larger sources of power became available and better and larger electrodes were necessary. The names of early experimenters in the electric field are also a part of electrode history, and those connected with arc lighting are especially prominent. The real necessity of larger electrodes came with the development of the electric furnace. Heroult, Braun, Zellner, and Hardmuth are names inseparably linked with the development of electrodes in Europe, while in America, Charles F. Brush and Washington H. Lawrence did most to make the production of electrodes a real business. Lawrence first used petroleum coke, then a nearly worthless by-product of one of the oil refineries.

After 1900 the production of suitable electrodes a few inches in diameter was no novelty, but Heroult's requirements of electrodes for his furnaces, which had capacities as large as 15 tons, changed the picture; and thereafter development for some years was rapid as the need for electrodes increased immeasurably.

Manufacturing Process

The process of manufacturing electrodes has not changed radically since early dates in the art; still a brief description of the methods of making carbon and graphite electrodes may be of interest. The chief raw materials are high-grade anthracite coal selected primarily for strength of particle, petroleum coke of low ash content, and hard and soft pitch. All of these materials are used in making carbon electrodes, the latter ones in making "coke" electrodes which are to be graphitized and for the carbon electrodes used in the aluminum industry. Both the anthracite coal and petroleum coke are treated at very high temperature to drive off volatile matter and induce shrinkage, but primarily to reduce the electrical resistivity to a low value. After

calcination, both materials are ground to predetermined sizes, depending upon the size of electrode to be made, and mixed with exact quantities of pitch in heated mixers.

The green mix may be extruded through dies under high pressure or molded under pressure to form the green electrodes in any one of the many sizes now required by a varied trade. The green electrodes must be made to an exact size with proper allowances for the shrinkage that occurs in the baking and graphitizing processes. The dies are machined most accurately—in fact, usually hand finished to templates—as the flow of materials through them must be controlled exactly to give a suitable finished product.

The green electrodes are packed in furnaces surrounded by fine coke, which supports them during the preliminary softening period as the heat is applied, and are baked to a final temperature of 1,000 deg C, the temperature being raised gradually to the maximum. Baking and after-cooling requires up to 5 weeks' time. After baking, the electrodes are cleaned by hand to remove the packing coke, and are inspected carefully for every one of a possible dozen or more faults. The coal carbon electrodes are sent to storage or to the threading and finishing department. The coke electrodes are ready to be graphitized.

The graphitizing process invented by E. G. Acheson is generally familiar. In this process the carbon material of electrodes is wholly changed into graphitic carbon through raising it to a temperature of at least 2,200 deg C by the heat generated by passing current through the material, which acts as a resistance body. The material is packed closely in large open furnaces and covered with coke. The current is supplied through huge contacts at the furnace ends; by manipulation of the current control the temperature is regulated and gradually brought to the desired maximum.

The complete cycle, packing, graphitizing, cooling, and unpacking, requires from a week to 10 days. After slow cooling the electrodes are cleaned and stored, or machined, as required for the various purposes for which they are to be used.

Electrode Specifications

There are certain definite requirements that all electrodes, carbon or graphite, should meet. First, they should be formed properly within the limits of the art, the usual specifications being ± 2 per cent of the dimensions for diameter or side; they should be straight, meeting a specification that the distance from a chord to the arc of the electrode should not be more than 0.5 per cent of the length. The electrodes should be of high density, and the usual manufacturing specification is that the apparent density shall not be less than 1.50 for carbon electrodes, and 1.51 for graphite electrodes. They should not show signs of coring or laminations. The surfaces should be clean and free from pits or blow holes, as well as relatively free from "alligator" markings. It is not customary in the trade to impose resistance specifications, though manufacturers inspect their own electrodes on that basis. The operator rarely is interested in the exact resistivity, his criticism being based upon performance in his own operation, which of course is influenced by whether or not the electrodes have suitably low resistivity.

Both carbon and graphite electrodes are made in a wide variety of shapes and sizes for innumerable uses. Round electrodes vary from $^1/_{16}$ in. in diameter and 12 in. long to 18 in. in diameter and 72 in. long for graphite, and up to 40 in. in diameter and

Extruding a carbon electrode 40 in. in diameter

110 in. long for carbon. It takes 500 of the $^1/_{16}$-in. size to make a pound, while the largest size mentioned weighs, 7,500 lb with its connecting pin. Rectangular electrodes have been made weighing up to 8,500 lb each.

Carbon and graphite manufacturers have a wide range of dies for manufacturing electrodes of various sizes, and any shape within wide limits that can be extruded or molded can be made. However, if time is an important element, any one contemplating the use of formed carbon or graphite will do well to consult the manufacturer to determine what sizes are in stock as 2 months are required to make carbon electrodes and 3 months to make graphite electrodes, even when the dies are available.

Applications of the 2 Types of Electrodes

For practically all electrolytic operations, graphite electrodes are preferable to carbon because of the much more rapid oxidation of carbon in the electrolyte as compared with graphite. In most electrolytic work carbon electrodes are wholly unsatisfactory.

For electrothermic work the division of the kinds of electrodes among the several types of operations is not so clear cut. All aluminum furnaces or pots use carbon electrodes, and this industry is by far the largest user of electrodes since about $^3/_4$ of a pound of electrode is used to produce every pound of aluminum. In fact, the aluminum industry consumes more electrodes alone than all other types of operations. The use is so large that these industries in the United States and Canada manufacture for themselves practically all of the electrodes they need. The carbide industry is another large user of electrodes, and practically without exception all carbide furnaces operate on carbon electrodes. Likewise, the ferro-alloy industry uses carbon electrodes almost without exception, though for some of the higher grade alloys, particularly those that must contain minimum amounts of carbon, graphite electrodes are used.

The nonferrous industry uses graphite electrodes exclusively because the electric furnace most generally used for the production of nonferrous metals is equipped to use graphite electrodes only.

When the iron and steel industry is considered the matter becomes complicated. More than half of the tonnage of steel ingots produced by electricity comes from furnaces equipped with graphite electrodes, though more than half of the furnaces use carbon electrodes. This is because several of the larger furnaces use graphite. In the steel casting field the division is more even; but in the gray iron industry most of the furnaces use graphite electrodes, partly, at least, because one type of furnace uses graphite electrodes only.

There are reasons for the distribution of electrodes in the various industries mentioned, and of course, the primary one is cost, that is, the cost of electrodes per pound or per ton of product. In the production of aluminum, carbide, and ferro-alloys the electrodes last for days, and in some cases several weeks. The electrodes must carry power into the furnaces at the lowest cost, and must have a relatively large area of working surface; and since the electrodes are consumed mostly by oxidation, the electrode having lowest cost is most satisfactory. New electrodes are added so infrequently that the fact that carbon electrodes are necessarily much larger and therefore more difficult to handle than graphite electrodes that might serve, does not have any particular weight. The same comments apply in general to the ferro-alloy industry, but there are exceptions as mentioned previously in the case of special alloys where the higher cost of graphite is more than offset by other advantages.

In iron and steel furnaces new electrodes are added often, sometimes several times a day, so the fact that a graphite electrode need be only a little over half as large as a corresponding carbon electrode to carry the same power is of importance from the operator's point of view. Graphite electrodes are joined together more easily, and because of their lesser weight the furnace superstructure need not be designed as substantially. Graphite electrodes cost approximately twice as much as carbon electrodes per pound, and this would seem to give carbon electrodes a great advantage; however, in operations such as those in the steel and iron industry, approximately half as much graphite is used per ton of product as carbon, therefore the higher cost is offset by the lower consumption. Other factors enter in as well, and before the operator determines whether he will use carbon or graphite electrodes, a number of points should be considered.

Carbon electrodes having a larger end area melt down a larger proportion of the charge under them and there is less tendency to bore down through the charge. However, the large area may prove to be a disadvantage because the arc is brought nearer the side walls of the furnace and the refractory cost may be higher as a result. Still, the larger end area, since it better protects the arc, may prevent so much heat from being reflected against the roof and reduce that cost.

Table I—Electric Furnaces in the United States

Year	Ferrous	Nonferrous*
1910	10	
1915	41	
1920	323	60
1925	479	310
1930	560	525
1933	580	560

* Does not include induction furnaces.

Table II—Tons of Steel Produced by Electricity in the United States

Year	Ingots	Castings	Total
1910	51,000	1,300	52,300
1915	46,000	23,000	69,000
1920	346,000	155,000	501,000
1925	335,000	280,000	615,000
1930	307,000	305,000	612,000
1932	141,000	100,000	241,000

American Iron & Steel Institute Tables.

Since the diameters of graphite electrodes are much smaller than those of equivalent carbon electrodes, the graphite ones may be broken more easily by scrap caving in on them or by being struck by furnace bars when the charge is worked. This situation is offset by the fact that graphite electrodes are machined easily, and pieces recovered from the furnace can be rethreaded in any machine shop and used again. Carbon electrodes are very difficult to machine, and it is rare that any operator recovers broken pieces except by sending them back to the manufacturer. The fact that no joint compound is used in making up graphite joints, while that material is a necessity for carbon electrodes, may be a deciding factor in determining which type of electrode is used if the desire of the operator is considered.

The lesser weight of the graphite electrode may make the control apparatus more effective because there is less inertia to overcome when the electrodes move up and down. Larger carbon electrodes may prove just as active, however, as there is a greater area to make contact with the slag or metal. Graphite having a lower resistance, the loss of power in graphite electrodes would be less if the same sizes of graphite and carbon were compared; but since much smaller graphite electrodes are used, the power losses in the 2 types of electrodes will not be greatly different. The reverse of this statement applies to heat conductivity, for graphite has much higher heat conductivity than carbon; but a smaller size keeps the 2 losses about the same.

Carbon and graphite electrodes do not act quite the same in the furnace, and this is more noticeable in connection with high-grade steel than steel castings. As a result, whether one kind or the other is used may become a matter of the melter's preference. One operator will claim that slags are made and maintained more easily under carbon electrodes than under graphite, while an equally good man will claim the reverse. One melter will state definitely that there is more chance of carbon pick-up if carbon electrodes are used in making special steels having a low carbon requirement, while another man making the same steel will *prefer* carbon electrodes. Such questions clearly demonstrate that while both types of electrodes have their proponents, still the adoption of one or the other is not necessarily based upon facts alone.

Another point that frequently enters into consideration is the matter of freight. For reasonably short hauls the fact that only half as much graphite is required as carbon to do the same work is not particularly important, for the difference in freight charges constitutes a small percentage of the total electrode cost; but for long hauls where the freight rate exceeds $1 per 100 lb, the differential may become quite a deciding factor.

As melting furnaces have become larger and the transformers back of them increased to a point where capacities of 10,000 to 12,000 kw are being used, furnace designers have been more inclined to use graphite electrodes since the carbon size required would be very large, 30 to 35 in. in diameter, and weights up to 4,000 or 5,000 lb per electrode. Such electrodes require very heavy superstructures which are expensive to build, and the electrode ports being very large the roof structure of the furnace may be weakened seriously or at least become difficult to maintain.

In the abrasive industry both carbon and graphite electrodes are used, the bulk of the material being produced by furnaces using carbon electrodes. For certain types of abrasives, such as those very light or even white in color, only graphite electrodes will serve.

It should be evident that no one can say offhand what type of electrode should be used for any of the industries except those producing aluminum and carbide. Many factors enter into the problem and each one must be given consideration before any conclusion is reached. Electrode manufacturers appreciate this situation and will be found willing to coöperate with any present user of electrodes to determine if he is operating under the best conditions, and to help a new operator determine which type of electrode is best suited to his problem. In many cases, furnace operators appreciating the situation have run tests on both types of electrodes and have tried more than one size to find out which combination gives the best operating results as well as the lowest cost. Lowest cost does not necessarily mean lowest electrode cost only, but rather the lowest combined cost of electrodes, power, refractories, and labor, because the kind and size of electrodes may influence all of the other factors.

Table III—Electrode Consumption in Pounds Per Ton of Product

Product	Carbon	Graphite
Nonferrous castings (net ton)		2.5–10
Iron castings, cold scrap (net ton)		5–10
Iron castings, duplex (net ton)		3–14
Steel castings (net ton)	9–20	5–12
Steel ingots (net ton)	17–30	10–20
15% Ferrosilicon (gross ton)	25–50	
50% Ferrosilicon (gross ton)	50–75	
80% Ferrosilicon (gross ton)	80–120	
High-silicon Ferrosilicon (gross ton)	150–300	
Calcium carbide (net ton)	30–200	
Aluminum (net ton)	1500–2000	

Electrode Consumption in Various Fields

The question of electrode consumption in the various industries is one that frequently brings forth arguments, and it is no wonder since so many factors enter into the problem. It would not be fair to compare a carbide furnace using 1,000 kw with one using 20,000 kw any more than it would be equitable to compare the electrode consumption of a furnace producing ordinary steel castings with one turning out the highest quality alloy steel. Every factor must be taken into consideration, the type of product, size of the furnace, as well as the ability of the operators. Indefinite figures on electrode consumption have little value, but in some cases they may be interesting.

As indicated before, consumption of electrodes in the aluminum industry ranges from 1,500 to 2,000 lb per ton. Electrode consumption for calcium carbide may be as low as 30 lb of carbon electrodes

per ton in large furnaces under advantageous conditions and as high as 150 to 200 lb of carbon electrodes in small and poorly designed furnaces. The consumption of electrodes in the ferro-alloy industry varies widely depending, of course, upon the material produced; it may be as low as 25 lb of carbon electrodes per ton for 15 per cent ferrosilicon, 50 lb per ton for 50 per cent ferrosilicon, 65 lb for 80 per cent ferromanganese, and 150 to 300 lb per ton for silicon alloys containing the higher percentages of silicon when these materials are produced under good operating conditions, but 2 or 3 times these figures for the same alloys produced under less advantageous conditions.

In the nonferrous industry, figures as low as $2\frac{1}{2}$ to 3 lb of graphite electrodes per ton are reported, but the average is undoubtedly nearer double that quantity and figures much higher often are reported.

In making high-grade steel, alloy steel, tool steel, stainless steel, etc., electrode consumptions as low as 17 lb of carbon electrodes per ton have been reported, but figures in that neighborhood are rather unusual and the average is probably nearer 25 lb. The figures for graphite are not as low as the expected $\frac{1}{2}$ of the figures for carbon because of the long finishing time required for these metals. During that period the electrodes are consumed largely by oxidation; and although this is less with the graphite electrode because of its smaller size, still the proportion is not maintained and graphite consumption of less than 12 lb per ton is unusual. In the steel casting field, the consumption of graphite electrodes is very nearly half that of carbon ones, with graphite consumptions reported as low as $4\frac{1}{2}$ to 5 lb comparing with carbon at 9 to 10 lb, and as high as 10 lb per ton, comparing with 20 lb for carbon. Such figures are influenced greatly by the rate of operation, that is, the number of heats per day and the amount of power put into the furnace per hour; and if the oxidation loss is proportionately great, as in the production of high-grade steel, the figures for graphite do not appear to as good advantage as they do when the bulk of the electrode consumption is accounted for by the transmission of power to the charge. Electrode consumption for iron may be as low as 3 lb per ton of graphite electrodes for furnaces charged with hot iron from the cupola, or may run as high as that for steel castings. Relatively few carbon electrodes are used in the gray iron industry, either duplexing or straight.

Conclusion

The number of users of carbon and graphite electrodes is increasing year by year, and the field of application is constantly widening. The future growth of the industry depends largely upon the use of the right electrode in the right place to secure the desired result, whether that be a new product or an old product made in a new way at a lower cost.

Electrode manufacturers have made clear their desire to coöperate at all times with electrode users, and particularly in the later years operators have shown more inclination to benefit by the assistance the manufacturers were willing to give.

Induction Motors as Selsyn Drives

The power Selsyn unit, an adaptation of the wound rotor induction motor, provides accurate remote control of angular motion, using only an electrical connection. The characteristics of these units are described briefly in this paper, and methods of calculating their performance are offered. Typical applications of Selsyn drives also are given.

By
L. M. NOWACKI
ASSOCIATE A.I.E.E.

General Elec. Co., Schenectady, N. Y.

THE SELSYN device is used for repeating or reproducing by remote electrical control angular motion, both as to speed and total angle. The word "Selsyn" is an abbreviation of the expression "self-synchronous" and indicates the normal use of the apparatus. The function of the Selsyn system is to transmit motion by electrical means between 2 points which cannot conveniently be interconnected mechanically.

The power Selsyn unit is an adaptation of the conventional wound rotor induction motor. The principle of operation is a familiar one. For simplicity, 2 identical 3-phase wound rotor induction motors will be considered. The stator windings are excited from a common power source, and the rotors electrically interconnected. One Selsyn unit is located at the point where the motion is generated and the other unit is located at the point where the motion is duplicated. Under these conditions, for each pair of poles, there is only one relative position of the rotors where the secondary voltages will be exactly opposed so that no current will circulate in the secondary windings. For other positions, a current will circulate in the rotor windings and torques will result tending to turn the rotors to that position where the voltages are again equal and opposite. If, therefore, one rotor is turned, the other rotor will tend to assume exactly the same position.

Selsyn units are synchronized at standstill by applying single-phase excitation. This introduces several problems which bear directly on the choice of control and winding connections. A study of

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the several synchronizing characteristics is important to the thorough understanding of the Selsyn drive. Both operating and synchronizing torques are expressed in terms of induction motor operating characteristics, thus enabling the direct translation of induction motor characteristics into synchronizing and operating data.

General

Selsyn devices were first built over 20 years ago. They were originally designed as instruments for transmitting and receiving an indication by an angular movement. In these applications the Selsyn receiver carried on its shaft only a very light dial pointer or possibly a cam. The characteristics of the Selsyn device, however, soon made it desirable that the receiver be capable of exerting enough torque to perform such work as operating relay contacts or turning a valve. Simultaneously with this development came also requests for Selsyn control systems where the units were required to rotate continuously at high speeds in addition to carrying mechanical loads. In the last 5 years, considerable progress has been made in extending the Selsyn principle to industrial machine drives.

The study of Selsyn behavior has not been given much attention in technical literature. Several papers were published in trade journals bearing, in the main, on application problems. The increasing popularity of the Selsyn drive made urgent a thorough understanding not only of the underlying principle of the Selsyn system, but, also, of the operating and synchronizing characteristics. It is the purpose of this paper, therefore, to describe briefly the behavior of the Selsyn units, to offer a convenient method for determining their characteristics, and to suggest the possible arrangements of the Selsyn tie.

Three-Phase Operating Characteristics

The 2 Selsyn units are connected as shown in Fig. 1. One unit, the transmitter, is driven. The second unit, the receiver, rotates in synchronism with the transmitter. The angle of deflection between the 2 rotors is given in electrical degrees and is designated by α. For any angle α and slip s, the transmitter and receiver torques, for rotation against the revolving field, are:

$$T_t = \frac{6.09\ V(I - I_m)}{\text{rpm}} \sin\theta \sin\alpha + T_0 \sin^2\frac{\alpha}{2} \quad \text{lb-ft} \tag{1}$$

$$T_r = \frac{6.09\ V(I - I_m)}{\text{rpm}} \sin\theta \sin\alpha - T_0 \sin^2\frac{\alpha}{2} \quad \text{lb-ft} \tag{2}$$

where

V is the line voltage
I is the induction motor current for slip s
$\cos\theta$ is the induction motor power factor for slip s
T_0 is the induction motor torque for slip s
I_m is the induction motor magnetizing current
rpm is the induction motor synchronous speed

The above factors, as designated, are determined for an induction motor operating at the given slip. Thus the induction motor characteristics may be translated directly into Selsyn drive performance.

Similarly, the currents:

$$I_t = \left(I_m \cos\frac{\alpha}{2} + jI \sin\frac{\alpha}{2}\right) \angle -\frac{\alpha}{2} \tag{3}$$

$$I_r = \left(I_m \cos\frac{\alpha}{2} - jI \sin\frac{\alpha}{2}\right) \angle +\frac{\alpha}{2} \tag{4}$$

The line current:

$$I_l = 2\left(I_m \cos^2\frac{\alpha}{2} + I \sin^2\frac{\alpha}{2}\right) \tag{5}$$

The rotor current:

$$I_R = jI_l \sin\frac{\alpha}{2} \tag{6}$$

All the currents are expressed vectorially. I_2 is the rotor induction motor current for slip s.

Torque characteristics are shown in Figs. 2 and 3.

The torque expressions of eq 1 and 2 consist of 2 components, the first a synchronizing component due to the rotor displacement, acting in the direction to decrease the angle, and a rotor loss torque, acting in the direction of the rotating field. On this account, the receiver torque is higher for rotation with the field and the transmitter torque for rotation against the field. The synchronizing torque is highest and the induction motor torque is lowest for slips greater than unity. Therefore, to obtain the highest synchronizing torque efficiency, Selsyn units are recommended for operation against field rotation. Similarly, to obtain the highest motor torque efficiency, the units are recommended for operation in the direction of field rotation. Rotation in the direction of the revolving field is much limited by the loss of synchronizing torque in the neighborhood of synchronous speed. Here, if there should be a sudden change in speed, particularly if the inertia of the system is appreciable, the transmitter and receiver may momentarily interchange their functions and possibly fall out of step. Operating in each direction with respect to the revolving field has its definite applications, all factors considered.

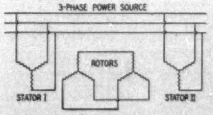

Fig. 1 (left). Connection diagram of 2 Selsyn units

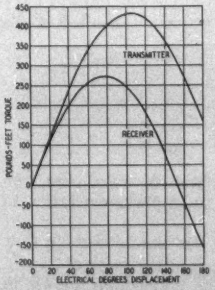

Fig. 2 (left below). Three-phase torque-angle characteristics at standstill, illustrated for 2 25-hp 8-pole 60-cycle 3-phase wound-rotor induction motors

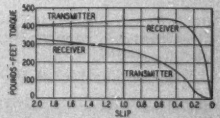

Fig. 3 (below). Three-phase maximum torque characteristics, illustrated for same motor as Fig. 2

Synchronizing of Selsyn Units

Selsyn units are synchronized at standstill. Single-phase power is applied first, and, after a momentary time delay, 3-phase excitation is applied. Although the units may be synchronized 3-phase, synchronizing single-phase is more practical and eliminates certain difficulties.

If 3-phase power is applied to the 2 units and if the initial angle of displacement is large, then, if the 2 units are unrestrained, they may tend to come up in speed in the direction of the revolving field. One machine will serve as a short circuit for the rotor of the other. The machines will not assume any definite speed but will fluctuate. If one unit is restrained, the other may come up to speed as an induction motor. With single-phase excitation, this occurrence is avoided, for the only torque existing is the synchronizing torque and continuous traction is not possible. Once the units are synchronized, 3-phase power is applied and the Selsyn tie is operative.

Single-phase excitation may be applied in one of 3 ways as shown in Figs. 4, 5, and 6, respectively. In all cases, the rotors are interconnected 3-phase. Each connection has its particular torque-angle characteristic.

The connection of Fig. 6 is suitable for synchronizing. The maximum torque is high and occurs in the neighborhood of 150 electrical degrees, the region where the synchronizing torque is least for the other connections. A possible objection to this connection, for some applications, is the rapid decrease in torque for angles less than 90 deg. A convenient arrangement, from an operating point of view, is the sequence of connections of Fig. 6 and Fig. 4. The connection of Fig. 4 prepares for the next step, the simultaneous application of the 3-phase excitation to all units.

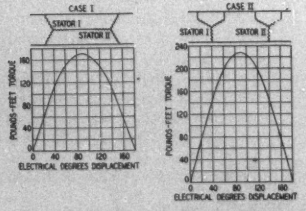

Fig. 4. Case I. Fig. 5. Case II. Fig. 6. Case II

Figs. 4, 5, and 6. Single-phase torque-angle characteristics at standstill for 3 different connections of same motors as illustrated in Fig. 2

The connection of Fig. 5 has the advantage that the magnetic flux is increased in the ratio of $2/\sqrt{3}$. The torque, like that of the connection shown in Fig. 4, varies as the sine of the displacement angle. For a given flux, the 2 connections have identical torque-angle characteristics at standstill. The connection of Fig. 5 has particular value when single-phase excitation is employed under running condition. This arrangement is poorest for induction motor action, but, on the same account, it is best for single-phase Selsyn operation.

Case I:

$$T = \frac{3.05\ V(I - I_m)\sin\theta}{\text{rpm}} \sin\alpha \text{ lb-ft} \tag{7}$$

$$I_1 = \frac{\sqrt{3}}{2}\left(I_m \cos^2\frac{\alpha}{2} + I\sin^2\frac{\alpha}{2}\right) \tag{8}$$

Case II:

$$T = \frac{3.50\ V(I - I_m)\sin\theta}{\text{rpm}} \sin\alpha \text{ lb-ft} \tag{9}$$

$$I_1 = \frac{2}{\sqrt{3}}\left(I_m \cos^2\frac{\alpha}{2} + I\sin^2\frac{\alpha}{2}\right) \tag{10}$$

The nomenclature is the same as for the 3-phase characteristics. The 3-phase induction motor values are determined for the slip of one and translated directly into single-phase synchronizing data.

The connection of Fig. 6 is a very special case and does not yield a simple solution. An analysis of this case is given in detail in Appendix II. For one thing, the magnetic flux varies with the displacement angle, increasing in the ratio of $\sqrt{2}$ for 90 deg displacement. The increased flux results in saturation and in an appreciable change in the several circuit constants. For this reason, the problem becomes involved and a rigorous solution difficult. It is to be noted that a definite second harmonic is present in the torque characteristic, which, in part, accounts for the decreased torque for the low values of displacement angle, and for the increased torque for the high values of displacement angle.

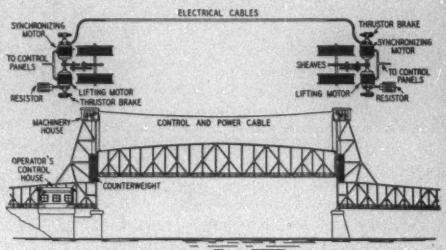

Fig. 7. Lift bridge operated by power Selsyn drive

Application of Selsyn Drives

A common and a simple application of Selsyn units is the tie of 2 parallel drives. An interesting arrangement is the synchronized drive for the long lift bridge, as shown in Fig. 7. The 2 ends of the bridge are lifted by separate motors. A power Selsyn unit is direct connected to each main motor and the 2 Selsyn rotors are electrically interconnected. The main motors, as well as the 2 Selsyn units, are energized from the same power source. The Selsyn units are first synchronized, and, after a short time delay, 3-phase power is applied to the 4 machines. By this tie, the 2 main motors are held

in step during acceleration and running, and the 2 ends of the bridge are lifted and lowered in synchronism. In addition to this feature, the synchronized drive embodies several other points of interest. By using 4 duplicate units, 2 for the main drives and 2 for the synchronous tie, the entire

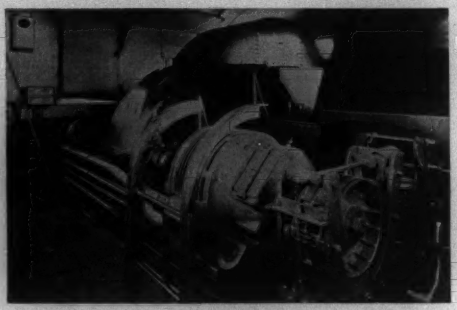

Fig. 8. Lifting motor and Selsyn unit on top of tower of bridge span

bridge may be lifted by one driving motor in case the other fails. Although this will impose a double load on the acting motor, nevertheless, in an emergency, this factor may prevent delay to railway traffic and navigation. Furthermore, the operating machinery is removed to the towers, the long-haulage cables and sheaves are eliminated, and thereby the weight of the total span is substantially reduced. A lifting motor and Selsyn unit of this type are shown in Fig. 8.

The Selsyn tie is applied to synchronize a group of unit motor drives, as shown in Fig. 9, for the straight-line high-speed newspaper press. The Selsyn unit is built integral with each driving motor, as shown in Fig. 10. The entire group of Selsyn elements is energized from a common power source and all the rotor windings are electrically interconnected. The Selsyn units are first locked in step and when driven by their respective motors, start simultaneously and rotate in synchronism. Any unbalance in power between the several driving motors is equalized through the Selsyn units. The movement of any individual rotor in this combination is accompanied by a simultaneous and equivalent movement of each of the other rotors. The inherent function, therefore, of such a group of Selsyn units is to hold in step and resist any external force to pull them apart. In the event of failure of any driving motor, continuity of operation is assured. The Selsyn unit, deriving its energy from the other Selsyn units, will carry the total load of the individual drive. Such loading of the Selsyn unit is not generally recommended for long periods, but in an emergency, this feature is desirable. The application of the Selsyn tie to the segregated drive for newspaper presses made for greater flexibility and convenience. It made possible the complete elimination of all forms of interconnecting drive shafts, gears, and bearings commonly associated with the usual form of press drives, with possible savings in cost of labor and maintenance.

Selsyn units are used to synchronize auxiliaries with the main drive in many industrial equipments. A Selsyn generator is direct connected to the main motor and the several auxiliary units are driven by separate Selsyn motors. This form of a Selsyn tie is shown in Fig. 11, for the poidometer drive. In mill operations, it is often necessary to vary the kiln speed, and it is desirable to vary the feed in like manner. The tube mills, for instance, are fed with 2 materials and it is necessary to have close regulation of the proportions of the materials in order to insure uniformity of product. Also, to obtain a maximum satisfactory output of the mill, it is important to have control of the quantity of material carried on the conveyors. By adapting the Selsyn tie to the poidometer drive, the kiln may be operated at any desired rate with a corresponding change in

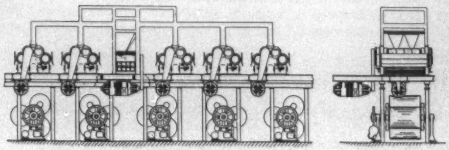

Fig. 9. Arrangement of motor drive with Selsyn tie-in, for straight line high-speed newspaper press

the conveyor speeds. In this manner, the proportions of the raw materials are fixed irrespective of the kiln speed.

The examples given are but a few of the possible applications of the Selsyn tie. A detailed and a specific description of the several drives is beyond the scope of the paper. The field of application is broad, ranging from fractional horsepower ratings for small auxiliary drives to main drives of 75 and

Fig. 10. Selsyn unit printing press drive

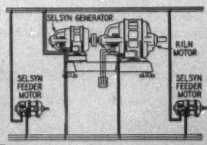

Fig. 11. Arrangement of Selsyn tie for poidometer drive

100 hp. The practicability of the Selsyn tie is fully recognized and its usefulness is more and more realized by the industrial engineer. The flexibility of the drive, the simplicity of operation, and the resulting economy will, no doubt, lead to the further adoption of the Selsyn principle to the synchronized motor drive.

Appendix I—Calculation of 3-Phase Characteristics

The equivalent circuit of 2 identical Selsyn units is the combined induction motor circuit for the 2 rotors in series. The electrical angle of displacement between the 2 rotors is equivalent to the same displacement between the Selsyn terminal voltages. The circuit constants are per phase star and are referred to the stator.

The equivalent circuit of Fig. 12 is resolved into the 2 component circuits of Fig. 13 and Fig. 14, respectively. The currents and voltages are determined for each component circuit, and, by superposition, are combined to give the currents and voltages of the original circuit.

The power transferred across the air gap is $E_g I_2 \cos \theta_2$, where E_g is the air gap voltage, I_2 is the rotor current, and θ_2 is the angle between them. In terms of the 2 component circuits, the power transferred is

$$P = P' + P'' \tag{11}$$

This is permissible, for the secondary current is common to the air gap voltages of the 2 component circuits.

$$P = E_g' I_2'' \cos \phi' + E_g'' I_2'' \cos \phi'' \tag{12}$$

where:

E_g' is air gap voltage of 1st component circuit
E_g'' is air gap voltage of 2nd component circuit
I_2'' is secondary current of 2nd component circuit
ϕ' is angle between E_g' and I_2''
ϕ'' is angle between E_g'' and I_2''

$$E_g' = \frac{jx_m E}{r_1 + j(x_1 + x_m)} \cos \frac{\alpha}{2}$$

$$= \frac{x_m E}{Z'} \cos \frac{\alpha}{2} \angle -\theta_1' + \frac{\pi}{2}$$

$$I_2'' = I_2 \sin \frac{\alpha}{2} \angle -\theta_2'' + \frac{\pi}{2}$$

$$\phi' = \theta_1' - \theta_2''$$

where:

$Z' \angle \theta_1'$ is the impedance of 1st component circuit
$I_2 \angle -\theta_2''$ is the induction motor rotor current for slip s
x_m is the induction motor magnetizing reactance

$$P' = \frac{x_m}{Z'} EI_2 \sin \frac{\alpha}{2} \cos \frac{\alpha}{2} \cos (\theta_1' - \theta_2'')$$

$$= \frac{x_m}{2Z'} EI_2 \sin \alpha \left[\sin \theta_1' \sin \theta_2'' + \cos \theta_1' \cos \theta_2''\right]$$

$$= \frac{EI_2 \sin \alpha}{2} \left[\frac{x_m(x_1 + x_m)}{(Z')^2} \sin \theta_2'' + \frac{r_1 x_m}{(Z')^2} \cos \theta_2''\right] \tag{13}$$

Equation 13 is rigorous, but, for convenience, it may be simplified by making the following assumptions:

$$\frac{x_m (x_1 + x_m)}{(Z')^2} = 1 - ab$$

$\frac{r_1 x_m}{(Z')^2}$ is negligible

$$I_2 \sin \theta_2'' = I \sin \theta_1'' - I_m$$

$$P' = \left[\frac{I^2 x_0}{2} - \frac{I_m^2 x_m}{2}\right] (1 - ab) \sin \alpha \tag{14}$$

where:

I is the induction motor current for slip s
I_m is the induction motor magnetizing current
x_0 is total induction motor leakage reactance
x_m is induction motor magnetizing reactance

$$ab = \frac{I_m x_0}{E}$$

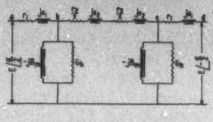

Fig. 12. The equivalent circuit of 2 identical Selsyn units

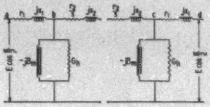

Fig. 13. The first component circuit

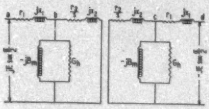

Fig. 14. The second component circuit

$$P'' = \frac{I_2^2 r_2}{s} \sin^2 \frac{\alpha}{2}$$

$$= \frac{I^2 r_2}{s} (1 - ab) \sin^2 \frac{\alpha}{2} \tag{15}$$

Combining eq 14 and 15, the Selsyn transmitter torque, for rotation opposite to the magnetic field, is:

$$T_t = \frac{21.1}{\text{rpm}} I^2 (1 - ab) \left[\left(\frac{x_0}{2} - \frac{a^2 x_m}{2}\right) \sin \alpha + \frac{r_2}{s} \sin^2 \frac{\alpha}{2}\right] \text{lb-ft} \tag{16}$$

Similarly, the receiver torque:

$$T_r = \frac{21.1}{\text{rpm}} I^2 (1 - ab) \left[\left(\frac{x_0}{2} - \frac{a^2 x_m}{2}\right) \sin \alpha - \frac{r_2}{s} \sin^2 \frac{\alpha}{2}\right] \text{lb-ft} \tag{17}$$

where:

rpm is the induction motor synchronous speed
r_2 is the induction motor secondary resistance
s is the induction motor slip
α is the displacement angle between rotors in electrical degrees

$$a = \frac{I_m}{I}$$

The transmitter current:

$$I_t = \left(I_m \cos \frac{\alpha}{2} + jI \sin \frac{\alpha}{2}\right) \angle -\frac{\alpha}{2} \tag{18}$$

The receiver current:

$$I_r = \left(I_m \cos \frac{\alpha}{2} - jI \sin \frac{\alpha}{2}\right) \angle \frac{\alpha}{2} \tag{19}$$

The line current:

$$I_l = 2 \left(I_m \cos^2 \frac{\alpha}{2} + I \sin^2 \frac{\alpha}{2}\right) \tag{20}$$

The rotor current:

$$I_R = jI_2 \sin \frac{\alpha}{2} \tag{21}$$

But for a small error, eq 16 and 17 may be written in the following form, as presented in the text:

$$T_t = \frac{6.09\ V}{\text{rpm}} (I - I_m) \sin \theta \sin \alpha + T_0 \sin^2 \frac{\alpha}{2} \text{ lb-ft} \tag{22}$$

$$T_r = \frac{6.09\ V}{\text{rpm}} (I - I_m) \sin \theta \sin \alpha - T_0 \sin^2 \frac{\alpha}{2} \text{ lb-ft} \tag{23}$$

THE SINGLE-PHASE SYNCHRONIZING TORQUES

The method employed for the 3-phase calculations may be extended for the first 2 cases of the single-phase excited units. The direct-phase and reverse-phase-sequence voltages are determined and the corresponding currents and torques calculated. For case I, the component voltages at standstill are:

$$E_D = E_R = \frac{E}{2} \tag{24}$$

Where D denotes direct-phase sequence and R reverse-phase sequence.

$$T_D = \frac{1}{4}\left[\frac{6.09V}{\text{rpm}}(I - I_m)\sin\theta\sin\alpha - T_0\sin^2\frac{\alpha}{2}\right] \text{ lb-ft} \tag{25}$$

$$T_R = \frac{1}{4}\left[\frac{6.09V}{\text{rpm}}(I - I_m)\sin\theta\sin\alpha + T_0\sin^2\frac{\alpha}{2}\right] \text{ lb-ft} \tag{26}$$

$$T = T_D + T_R = \frac{3.05V}{\text{rpm}}(I - I_m)\sin\theta\sin\alpha \text{ lb-ft} \tag{27}$$

Similarly for case II:

$$E_D = E_R = \frac{E}{\sqrt{3}} \tag{28}$$

And

$$T = T_D + T_R = \frac{3.50\ V(I - I_m)}{\text{rpm}}\sin\theta\sin\alpha \text{ lb-ft} \tag{29}$$

The nomenclature is the same as for the 3-phase case. All the factors are determined for locked-rotor 3-phase induction motor.

Appendix II—Single-Phase Characteristics of Case III

The stators and rotors are connected as shown in Fig. 6. Deflecting one rotor from the other is equivalent to displacing the 2 stator fields by the same angle. If the angle of deflection between the 2 rotors is α, the stators may be represented diagrammatically as shown in Fig. 15.

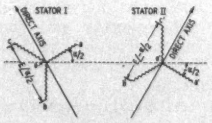

Fig. 15. Schematic diagram of the 2 single-phase fields

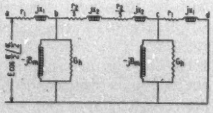

Fig. 16. Three-phase impedance offered to the in-phase voltage component

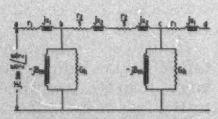

Fig. 17. Three-phase impedance offered to the quadrature voltage component

Let voltage $E \angle -\alpha/2 = 0$. Refer $E \angle \alpha/2$ to the direct axis of stator II, namely $(E \angle \alpha/2)(\cos\alpha - j\sin\alpha)$. $E\cos\alpha \angle \alpha/2$ induces no voltage in phase $0'a'$. For this component, the short circuit may be considered 3 phase. The impedance offered to $E\cos\alpha \angle \alpha/2$ is a balanced 3-phase secondary impedance as represented by the circuit of Fig. 16.

$-jE\sin\alpha \angle \alpha/2$ induces no voltage in phases $0'b'$ and $0'c'$. For this component, the 2 phases may be considered open circuited. The impedance offered to $-jE\sin\alpha \angle \alpha/2$ is a balanced 3-phase secondary impedance represented by the circuit of Fig. 17.

Similarly let $E \angle \alpha/2 = 0$. Refer voltage $E \angle -\alpha/2$ to the direct axis of stator I, namely $(E \angle -\alpha/2)(\cos\alpha + j\sin\alpha)$. The impedance of Fig. 16 and Fig. 17 is now offered to $E\cos\alpha \angle -\alpha/2$ and $jE\sin\alpha \angle -\alpha/2$, respectively.

The several voltages are further resolved into the in-phase and quadrature components:

Voltages at a	Voltages at d
$E\cos\alpha\cos\alpha/2$	$E\cos\alpha\cos\alpha/2$
$jE\cos\alpha\sin\alpha/2$	$-jE\cos\alpha\sin\alpha/2$
$-jE\sin\alpha\cos\alpha/2$	$jE\sin\alpha\cos\alpha/2$
$E\sin\alpha\sin\alpha/2$	$E\sin\alpha\sin\alpha/2$
$jKE\sin\alpha\cos\alpha/2$	$-jKE\sin\alpha\cos\alpha/2$
$KE\sin\alpha\sin\alpha/2$	$KE\sin\alpha\sin\alpha/2$

Inspecting the 6 sets of component voltages, it may be noted that 3 pairs are in phase addition and 3 in phase opposition. One set of 3 operates on the open-circuit impedance of Fig. 13 and the other on the short-circuit impedance of Fig. 14. The 2 voltages are designated by E' and E''.

$$E' = E(\cos\alpha\cos\alpha/2 + (1 + K)\sin\alpha\sin\alpha/2) \tag{30}$$

$$E'' = jE(\cos\alpha\sin\alpha/2 - (1 - K)\sin\alpha\cos\alpha/2) \tag{31}$$

E' and E'' are single-phase voltages producing pulsating fields. The 2 pulsating fields are each resolved into the 2 rotating fields of direct and reverse-phase sequence which, at standstill, are $E'/2$ and $E''/2$.

As for case I and case II:

$$T = T_D + T_R = \frac{21.1}{2\ \text{rpm}} Eg' I_2'' \cos\phi' \quad \text{lb-ft} \tag{32}$$

where:

Eg' is the air gap voltage of the open circuit
I_2'' is the secondary current of the short circuit
ϕ' is the angle between Eg' and I_2''
rpm is the synchronous speed

The factor K is an impedance ratio. It is determined from the circuit of Fig. 17.

$$K = \frac{E_d}{E_a} \tag{33}$$

where E_a and E_d are the voltages at a and d, respectively.

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Corona Losses From Conductors of 1.4-Inch Diameter

A sequel to an earlier paper by Carroll and Cozzens concerning corona loss measurements for the design of transmission lines, this paper presents data resulting from comparative tests on 6 different designs of 1.4-in. conductor, the size selected for a 275-kv transmission line from Boulder Dam to Los Angeles. Data covers 3-phase, single-phase, and rain tests, and adds materially to the corona loss data previously reported.

By
JOSEPH S. CARROLL
ASSOCIATE A.I.E.E.
Director, Ryan Laboratory, Stanford University, Calif.

BRADLEY COZZENS
ASSOCIATE A.I.E.E.

THEO. M. BLAKESLEE
ASSOCIATE A.I.E.E.
Research Engineers, Dept. of Water and Power, City of Los Angeles, Calif.

FROM CORONA LOSS tests sponsored by the Los Angeles Department of Water and Power at the Harris J. Ryan high voltage laboratory at Stanford University[1] and other previous tests,[2] a corona loss formula was developed from which an economic diameter of 1.4 in. was determined for the department's 275-kv transmission line from Boulder Dam to Los Angeles. In response to the specifications for the 1.4-in. conductor, the 6 different designs shown in Fig. 1 were submitted by various manufacturers.

During 1933 the Department of Water and Power conducted further tests at the Ryan laboratory, using factory samples of each of the 6 designs, as a result of which the following conclusions were reached:

1. The importance of the die grease as affecting corona loss was further emphasized by the 1933 tests.

2. Complete grease removal either by thoroughly washing, or by washing in connection with a period of aging, is necessary to obtain consistent corona loss data.

3. Both gasoline and soap and water washings are necessary to accomplish complete cleaning of the cables.

4. Rain greatly increases the corona loss from conductors, but there appears to be little correlation between loss and rainfall rate.

5. While the differences in the corona loss for separate types of 1.4-in. stranded conductors are slight, the tests indicate that the size of the outside strands and the neatness of the stranding are factors affecting corona.

6. Smooth, properly formed segment conductors have a lower corona loss than stranded conductors of the same diameter.

7. The smoothness of the segments is of prime importance in eliminating loss from a segment type of conductor.

Details of procedure and results are given in the following text and illustrations.

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, Jan. 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Nov. 9, 1933. *Not published in pamphlet form.*

1. For all numbered references, see list at end of paper.

Test Arrangement and Procedure

Samples were furnished for a 3-phase test line 700 ft long and were erected in 2 equal spans of horizontal configuration, 30-ft spacing, 30-ft ground clearance and 16-ft sag. With slight modifications, the test arrangement was the same as that used in the 1931 tests, and the measurements were made with the same equipment and in the same manner as previously described.[1]

In each insulator string supporting the test line, 20 units of 10-in. diameter were used. The line end of each string was shielded with a torus of 3-ft outside diameter made up of 6-in. stove pipe elbows and the ground end of each string was shielded with the 2-ft aluminum radio shield previously described.[2] Suspension clamps were shielded further by smooth housings 6-in. in diameter. Fig. 2 shows the dead-end assembly and the suspension shield fittings. Insulators thus shielded showed no visible corona at line voltages up to 600 kv under dry weather conditions.

Although the set-up was free from insulator loss for the dry conditions, previous experience[2] indicated that the loss over the insulators when damp could not be ignored. One duplicate dead end and one duplicate suspension string were erected in the open near the line and power loss over these strings was measured simultaneously with the line loss. When for a line voltage of 395 kv the loss over the two strings was greater than 10 watts, the values as read were multiplied by the proper value and subtracted from the total power to give the correct corona loss.

In the two cases where loss measurements were obtained during rain, a burette tube equipped with a large mouthed multiplier was placed in proximity to the line and, from readings taken on this tube at definite intervals, curves were drawn from which the rainfall rate could be determined.

Past experience[1,2,4,7] has shown that die grease or other lubricants used in the manufacture of cable greatly affect the corona loss. In most of the tests here described the loss measurements were obtained on the conductor as received from the factory. As

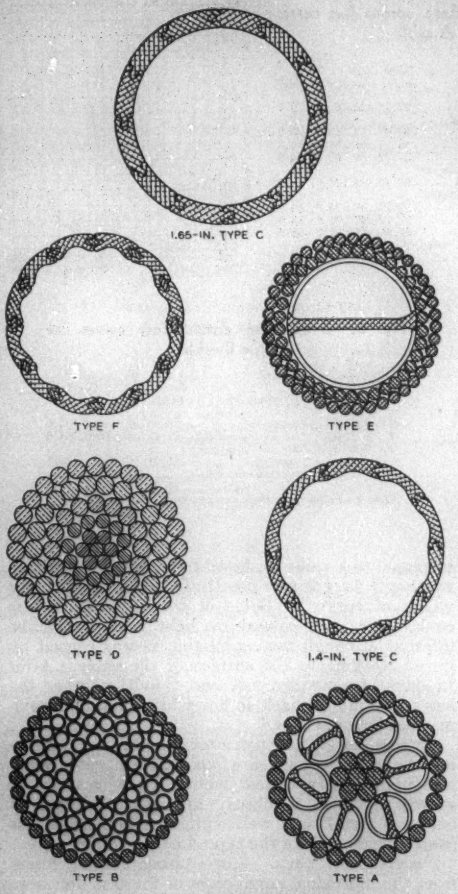


Fig. 1. Sections of the various designs submitted for the large sized conductors required for the 275-kv line to carry Boulder Dam power to the City of Los Angeles

Type A. A copper conductor made up of a 7-wire strand surrounded by 6 twisted I-beams with a single layer of round wires over all. The outer layer is composed of 30 wires each 0.125 in. in diameter having an 11-in. right hand lay.

Type B. A copper conductor with an inner structure composed of a central tube surrounded by layers of smaller tubes with a single outside layer of 37 solid round wires each 0.104 in. in diameter and with a 14-in. left hand lay.

Type C. A hollow copper conductor made up of 10 segments with a 28-in. right hand lay. The segments are interlocked, forming a self supporting structure presenting a smooth outer surface. The 1.65-in. type C cable was of similar construction, but made up of 12 segments having a 34-in. right hand lay.

Type D. An aluminum conductor steel reinforced, having 28 outside strands each 0.1355 in. in diameter with a 14.5-in. left hand lay.

Type E. A copper conductor of the regular twisted I-beam construction having 2 layers of round wires, the outside layer made up of 37 wires each 0.1077 in. in diameter with a 10.9-in. right hand lay.

Type F. A hollow copper conductor made up of 12 segments with a 19-in. right hand lay. The segments are grooved to fit an oval wire which holds them together. The surface of each segment has a shorter radius of curvature than that of the conductor, a feature which tends to "submerge" the seams between strands.

in previous tests, the cables then were lowered and washed with gasoline followed by a scrubbing with soap and water and a thorough rinse with clear water. A loss measurement followed this treatment. After weathering for some time, the cables were given an additional cleaning with fiber brushes and clear water and again tested. This procedure was modified for some particular cables and situations; for example, to determine if it was necessary to follow the gasoline washing with the soap washing and water rinsing, the type *B* cable was tested after the gasoline washing and again after the soap-and-water treatment.

The first sample tested in the 1933 series was the 1.65-in. type *C* conductor. Special tests on this cable included measurements taken hourly over a 19-hr period; also during rain, and before and after the application of a dust layer (half clay and half feldspar) to the cable. Four days later grease was

Fig. 2. Dead end insulator assembly and detail of suspension string shield used in tests

Fig. 3. Interior grease spreading over exterior surface of 1.65-in. type C (tubular segment) cable

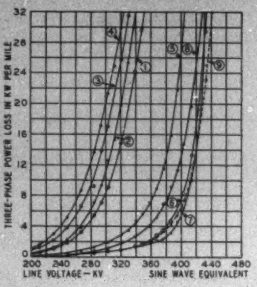
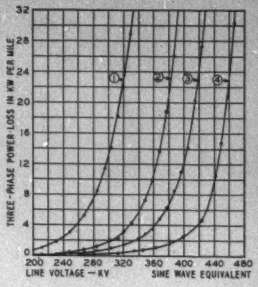


Fig. 4 (left). Three-phase corona loss curves for type A cable

Curve No.	Date	Condition	Barom. In. Hg	% Rel. Humid.	Temp. Deg F Air	Temp. Deg F Cable
1	3-21-33	As Received (paper wrapped)	29.91	32	62.0	73.0
2	3-22-33	1 day later	29.86	52	53.0	60.0
3	3-24-33	3 days later	30.14	62	55.0	59.5
4	3-30-33	9 days later	30.02	58	60.0	70.0
5	4- 3-33	After gasoline, soap and water washing	29.78	53	71.5	82.0
6	4-12-33	After clear water washing	29.99	31	73.0	86.0
7	4-14-33	2 days later	29.79	27	77.5	83.0
8	4-18-33	6 days later	29.85	45	57.0	66.0
9	5- 9-33	After 2d clear water washing	29.85	50	53.0	58.0



observed spreading over the surface of the cable from the segment interstices. Fig. 3 shows how plainly this spreading grease was indicated by the dust layer.

The construction of the type *C* and type *F* conductors permitted the circulation of gasoline through their interiors. Profiting by the experience with the 1.65-in. type *C* conductor, the 1.4-in. types *C* and *F* conductors were flushed prior to the regular exterior cleaning by circulating gasoline through each sample for from $1^1/_2$ to 2 hours, followed by air circulation for an equal period. The effect of this cleaning on the corona loss was so marked that the 1.65-in. type *C* cable was retested with gratifying results after similar treatment.

Single phase measurements obtained on single conductors with the other 2 conductors grounded helped to emphasize the importance of surface condition, especially grease, as it affects corona loss.

Tests on Type *A* Conductor

Three-Phase Tests. The range of power losses revealed by a series of 3-phase tests on type *A* cable is shown by the curves of Fig. 4. The cable was brushed with fiber brushes at the factory and upon receipt at the laboratory the three lengths were taped with heavy wrapping paper to preserve the surface as received. Loss measurements obtained on this cable 1, 2, 4, and 10 days after it was erected are reflected in curves 1 to 4 which show the progressive shift of the loss curves toward the low voltage abscissa due to the grease spreading over the surface from within the cable.

Curve 5 gives the loss on this same cable immediately after a gasoline, soap and water washing, and reveals that a shift of 60 kv was accomplished by the cleaning. Loss measurements taken 1, 5, and 8 days after the same washing gave less than 5 kv shift from curve 5 and are not plotted.

Nine days after the same washing the cable was washed in clear water and again tested. The results as given by curve 6 show a shift of from 40 to 50 kv from curve 5. Curve 7 shows the loss on this same cable 2 days after the clear water wash as being slightly less at the bend portion of the curve. A brisk wind during the time curve 7 was obtained was the only thing to make it different from curve 6. Six days after the clear water wash the loss had

Fig. 5. Three-phase corona loss curves for type B cable

Curve No.	Date	Condition	Barom. In. Hg	% Rel. Humid.	Temp. Deg F Air	Temp. Deg F Cable
1	5-11-33	As received	29.96	60	56.0	61.0
2	5-12-33	After gasoline washing	29.97	61	58.0	64.0
3	5-16-33	After soap and water washing	29.95	62	59.5	62.0
4	5-31-33	After clear water washing	29.83	40	65.5	70.0

Curve 4 based on single phase measurements on lines 1 and 2.

increased to a value as shown by curve 8, and within another 2 days it was practically identical with the values of curve 5. Some of this increase in loss could have been caused by light rain during the interim[2] although more probably it was caused by grease working to the surface of the cable. After 12 days of generally cool and cloudy weather the loss curve moved back to lower loss values approximating those of curve 7.

Approximately a month after the clear water washing the cable was given a second clear water wash and immediately tested again. These results, as shown in curve 9, closely approximate those of curves 6 and 7, and well represent the corona loss from a clean cable of the type *A* construction.

Single-Phase Tests. Single-phase corona losses from the individual conductors of the test line were obtained for 3 conditions: (1) as received, (2) after gasoline, soap and water washing, and (3) after first clear water washing. As received, the loss on line 3 (the conductors of the test span were designated lines 1, 2, and 3 with line 2 the center conductor) was appreciably greater than the loss on lines 1 and 2. After the gasoline, soap, and water wash the difference in loss between individual conductors was less, and was decreased further after the clear water wash. Part of these variations may be due to difference in the cable surface, but, from tests on this and other types of conductor, it is apparent that the principal difference is in the amount of grease on the cable surface.

Tests During Rain. Inasmuch as previous measurements[3] have indicated a large increase in corona loss during rain, a few single phase measurements on the greasy type *A* cable as received from the factory were made during rain periods with concomitant measurement of rainfall. The measurements were

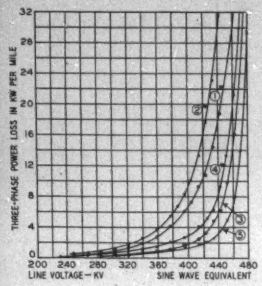


Fig. 6. Three-phase corona loss curves for 1.4-in. type C conductor

Curve No.	Date	Condition	Barom. In. Hg	% Rel. Humid.	Temp. Deg F Air	Temp. Deg F Cable
1	6- 2-33	As received (paper wrapped)	29.88	.44	.61.0	.66.0
2	6- 5-33	4 days later (paper wrapped)	29.81	.56	.65.0	.68.0
3	6- 8-33	After gasoline, soap and water washing	29.91	.25	.76.0	.88.0
4	6-22-33	14 days later	29.84	.42	.72.0	.76.0
5	6-23-33	After clear water washing	29.86	.36	.70.0	.78.0

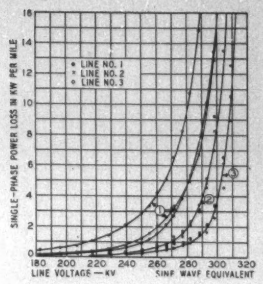


Fig. 7 (right). Single-phase corona loss curves for 1.4-in. type C cable

Curve Set	Date	Condition	Barom. In. Hg	% Rel. Humid.	Temp. Deg F Air	Temp. Deg F Cable
1	6- 2-33	As received	29.91	.37	.63.0	.74.0
2	6- 8-33	After gasoline, soap and water washing	29.91	.34	.75.0	.86.0
3	6-23-33	After clear water washing	29.86	.46	.68.0	.76.0

made at 185 kv to ground on line 1, simultaneously taking readings of total line loss, of insulator loss, and on the rain gage. The loss did not show the expected variation with rainfall rate because, although this value varied from as much as 0.12 in. per hour to less than 0.005 in. per hour, the corona loss varied only from 40 kw per mile to 32 kw per mile. The corresponding single phase, dry weather loss on the same conductor was approximately 2 kw per mile. The foregoing wet weather values were corrected for insulator loss as previously described.

Tests on Type *B* Conductor

Three-Phase Tests. Power losses for the type *B* cable, as revealed by 3-phase tests are shown by the curves of Fig. 5. This cable received no cleaning at the factory and hence, though well stranded, was very greasy. Erected without the protective paper covering, and as received from the factory, this cable had a corona loss as shown in curve 1. Washed in gasoline only the day after erection, the cable showed (curve 2) a shift of about 70 kw from the "as received" condition. Four days later the cable was given the soap and water cleaning, which caused a further shift of 35 kv (curve 3). A loss curve taken two days later showed a shift of less than 5 kv and is omitted. The fact that each treatment gave a decided shift in the loss curves indicates that both the gasoline and the soap and water cleaning are necessary. It being necessary to accelerate the tests, two lengths of type *B* cable were left in position as lines 1 and 2 and a single length of type *E* cable was substituted for line 3, requiring the remaining measurements on type *B* cable to be made single phase.

Three-phase power loss may be approximated from the single phase measurements, the conversion involving the premise that corona loss is dependent upon the voltage gradient surrounding the conductor. Since, for the same conductor under different conditions equal charging currents indicate equal gradients, it should be true that equal charging currents would be accompanied by equal corona losses. From a straight line relation of charging currents with respect to voltage for single phase and 3-phase conditions, the equivalent single phase and 3-phase voltages corresponding to any particular value of charging current and, by premise, to any particular value of corona loss may be obtained. Because of less definite factors than gradient (space charge[5]), three-phase loss curves obtained by this method are generally lower than curves from actual 3-phase tests, but the accuracy is sufficient to allow conversion when 3-phase data are lacking. Curve 4 of Fig. 5 gives the 3-phase results obtained by the above conversion method on the type *B* cable after the clear water rinse. This additional rinse shifted the loss approximately an additional 55 kv.

Single-Phase Tests. Single-phase measurements made on the individual conductors as received, showed lines 2 and 3 to have similar loss values with line 1 having a lower loss value equivalent to a shift of from 25 to 30 kv. After the gasoline washing, the curves for all 3 lines showed less than a 10-kv separation. A further test after the soap and water wash showed lines 1 and 3 to have practically identical loss, with line 2 having the greater loss by a voltage shift of about 10 kv.

Tests on 1.4-In. Type *C* Cable

Three-Phase Tests. Results of 3-phase tests on 1.4-in. type *C* cable are shown in the curves of Fig. 6. This cable was washed exteriorly at the factory, and at the laboratory was taped with wrapping paper to protect the surface, but prior to erection the paper became discolored by grease working to the surface from within the conductor. Loss measurements taken on the cable in this condition are given by curve 1. Four days after erection a second loss measurement gave considerable higher loss values (curve 2) as a result of the grease spreading over the cable surface. Inasmuch as the exterior cleaning obviously would not have been sufficient for a satisfactory test, the cable was given an interior flushing as already described.

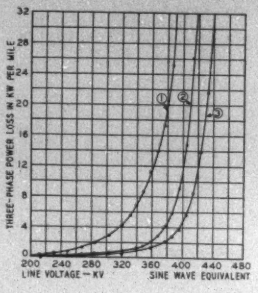


Fig. 8 (left). Three-phase corona loss curves for type D cable

Curve No.	Date	Condition	Barom. In. Hg	% Rel. Humid.	Temp. Deg F Air	Temp. Deg F Cable
1	7–6–33	As received	29.68	45	77.0	90.0
2	7–11–33	After gasoline, soap and water washing	29.75	26	93.0	102.0
3	7–27–33	After clear water washing	29.63	31	86.0	100.0

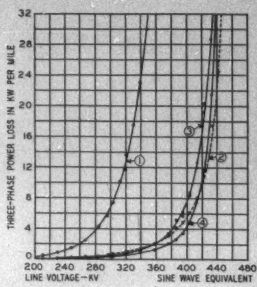


Fig. 9. Three-phase corona loss curves for type E cable

Curve No.	Date	Condition	Barom. In. Hg	% Rel. Humid.	Temp. Deg F Air	Temp. Deg F Cable
1	8–2–33	As received	29.90	50	74.0	84.0
2	8–3–33	After gasoline, soap and water washing	29.92	52	71.0	
3	8–11–33	8 days later	29.71	36	81.0	94.0
3	8–16–33	13 days later	29.88	51	81.0	95.0
4	8–16–33	After clear water washing	29.77	36	90.0	100.0

Curve 3 gives the corona loss after the interior flushing and the exterior gasoline, soap and water wash. It will be observed that the shift at the bend portion of the curve is greater than at the higher voltage values, showing that the grease is primarily effective in *starting* corona. Loss curves were obtained 5 and 14 days after this cleaning and the latter curve is presented as curve 4.

As with the other types of cable, a clear water rinse shifted the loss to still lower values (curve 5). A test made 7 days later gave a loss curve identical with curve 3, whereas a further test made 12 days later and under adverse weather conditions showed the loss to have increased until the curve was practically identical with curve 4. This latter shift can be explained by the results of study by graduate students at Stanford University[6] which showed that the amount by which corona loss varies with increased humidity is dependent upon the foreign matter on the surface of the conductor. Thus the 12-day accumulation of dust and other foreign matter on the 1.4-in. type *C* cable gave a higher loss with the high humidity than would be encountered under dry weather conditions.

Single-Phase Tests. The 3 sets of curves in Fig. 7 show the corona loss of individual conductors (1) as received, (2) after a gasoline, soap and water wash, and (3) after further clear water rinse. While the curves for the cable as received show a difference in excess of 15 kv, it may be seen that after each washing treatment the separation between individual samples is very slight.

Tests on Type *D* Cable

Three-Phase Tests. Results of 3-phase tests on type *D* cable are shown in the curves of Fig. 8. Although this cable was given the regular factory cleaning normally applied to this type of conductor, it still carried considerable grease. To prevent accretion of dust and dirt, the cable was prevented from coming in contact with the ground during erection. Curve 1 gives the loss as erected, and tests made 4 days later gave practically the same values.

In an attempt to clean this cable thoroughly, practically twice the gasoline used on other cables was used and the cable was rinsed in gasoline prior to the soap and water washing. Curve 2 gives the corona loss after this washing and, as with the type *C* cable, shows the shift to be greatest at the bend portion of the curve. Tests 9 and 15 days after washing showed little shift from curve 2. Even with this thorough initial cleaning, a subsequent washing with clear water shifted the loss curve still farther, as shown by curve 3. Single-phase loss measurements taken 5 days after the clear water washing showed little difference from those taken immediately after that washing.

Single-Phase Tests. This cable was no different in action under single-phase measurements than any others. Differences between individual conductors when initially tested became less after the gasoline, soap and water wash and still less after the clear water rinse.

Tests on Type *E* Cable

Three-Phase Tests. Curves of Fig. 9 show the results of 3-phase tests on type *E* cable. This cable was cleaned at the factory with rotating brushes, and was erected without protective covering. Curve 1 shows the corona loss on this cable as received. To accomplish a thorough cleaning of this cable, 2 gasoline rinses followed the regular brushing with gasoline. Tests made after the gasoline, soap and water washing showed a shift of more than 100 kv, as indicated in curve 2. Measurements made 8 and 13 days later gave values as shown by curve 3, with little difference between the 2 measurements. That the initial cleaning was thorough is shown by the slight shift (curve 4) following the final washing with clear water.

Single-Phase Tests. Contrary to the condition with the other cables, the loss on the individual conductors for the type *E* cables as received was practically identical. After gasoline, soap and water

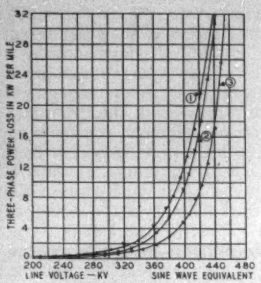


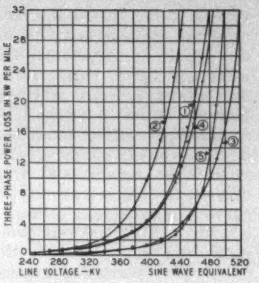
Fig. 10. Three-phase corona loss curves for type F cable

Curve No.	Date	Condition	Barom. In. Hg	% Rel. Humid.	Temp. Deg F Air	Temp. Deg F Cable
1	8-18-33	After gasoline, soap and water washing	29.73	57	73.0	84.0
2	8-28-33	10 days later	29.81	44	70.0	75.0
3	8-29-33	After clear water washing	29.81	48	73.0	82.0

Curves 2 and 3 based on single-phase measurements on lines 2 and 3

Fig. 11 (right). Three-phase corona loss curves for 1.65-in. type C cable

Curve No.	Date	Condition	Barom. In. Hg	% Rel. Humid.	Temp. Deg F Air	Temp. Deg F Cable
1	2- 1-33	2 days after gasoline, soap and water washing	30.13	60	45.5	58.0
2	2-21-33	22 days after gasoline, soap and water washing	29.99	45	62.0	73.0
3	2-24-33	After clear water wash	30.13	25	60.5	67.0
4	3-18-33	22 days after clear water wash	30.22	51	59.0	69.0
5	9- 7-33	After second gasoline, soap and water wash	29.57	20	82.0	94.0



washing there was a slight difference that did not change appreciably with the clear water rinsing.

Tests on Type *F* Conductor

Three-Phase Tests. Results of 3-phase tests on type *E* cable, of tubular construction, are reflected in the curves of Fig. 10. This cable received no cleaning at the factory, but was flushed with gasoline before erection. Because grease continued to ooze from the cable a second flushing was required, after which the regular exterior gasoline, soap and water treatment was given. The resulting loss is given by curve 1. An accident prevented further 3-phase tests being made, so the remainder were made single phase and converted as previously described.

Single-Phase Tests. The single-phase tests showed the characteristic difference in loss from individual conductors. After the clear water washing, some difference still existed between conductors 2 and 3, though they were free from grease. Single phase loss measurements taken 10 days after the soap and water cleaning, and converted to 3-phase values, are given by curve 2. The results after the clear water wash as obtained by the same method are given by curve 3.

Tests on 1.65-In. Type *C* Conductor

Three-Phase Tests. Curves of Fig. 11 reflect the results of tests on the 1.65-in. type *C* tubular conductor. This was the first conductor tested during 1933. At the close of the tests on the 1.4-in. cables, the larger cable was flushed with gasoline and given a second gasoline, soap, and water washing. The cable was initially erected in wet weather so was given the normal exterior gasoline, soap and water wash before testing. The first loss measurement (curve 1) was made 2 days after the initial washing, a slight rain occurring in the interim. Measurements obtained a day later showed a slightly lower loss, whereas those obtained 22 days after the initial washing gave appreciably higher losses (curve 2). This increased loss was found to result, first, from the spreading of grease over the cable surface from between the segments and, second, from the accumulation of bird dung on the cable. Consequently, the cable was washed with clear water and tested again (curve 3).

Tests made to determine the effect of dust on the cable surface showed that as long as the cable was dry the change in loss was negligible. Another test on the same cable made 22 days later however, yielded the results shown in curve 4, revealing that grease and more bird dung had accumulated. After this the cable was stored for 6 months and then flushed and rewashed with gasoline, soap and water, whereupon another test yielded the data shown in curve 5.

Tests made with loss measurements taken hourly over a 19 hour period were made immediately after the dust, grease, and bird dung were removed. Though previous experience had shown the loss to vary appreciably after nightfall and with increasing humidity, these tests showed a maximum shift in the loss curves of less than 20 kv, undoubtedly due to the absence of foreign matter on the cable as previously mentioned.[6]

Rain tests and single phase measurements on this cable exhibited nothing different from that mentioned with respect to other cables.

Recapitulation

After Gasoline, Soap and Water Washing. The corona loss curves for all cables tested in 1933 together with the 1.49-in. and 2-in. cables tested in 1931[1] are presented in Fig. 12. Type *A* (curve 1) shows the highest loss, possibly due to incomplete grease removal, difficulty in obtaining smooth stranding with the multiple I-beam construction, and larger diameter of strands in the outer layer. The type *B* cable (curve 2) appears to be slightly high for this type of cable, possibly due to incomplete cleaning. The type *D* cable (curve 3) having large strands and possibly being not completely clean, also is high. Curve 4 for the type *E* cable probably is the best that can be expected from a clean, well made cable of this diameter having small wire strands. The

type E cable shows a lower loss than the 1.49-in. stranded cable (curve 5) tested in 1931, possibly due partly to a less complete washing of the latter cable and partly to the fact that the type E cable was stranded better and was brush-cleaned at the factory. Curve 6 for the 1.4-in. type C conductor in a thoroughly clean condition shows the advantage of this type of conductor, from a corona loss standpoint, over conventional stranded cable of the same diameter. The segment type of conductor (type F, curve 7) shows loss values very close to those for stranded cables of the same diameter. Curve 8 shows the corona loss for the 1.65-in. type C conductor after being cleaned inside and out with gasoline and with the exterior soap and water washing. The loss for the 2-in. cable from previous tests, after the standard gasoline, soap and water wash, is given by curve 9.

After Clear Water Wash. Fig. 13 gives the corona loss curves for all the 1.4-in. conductors tested. These curves give a better laboratory comparison of corona loss performance than the conditions given in Fig. 12, although the latter curves probably represent more nearly the conditions that might be encountered in practice. The type A cable (curve 1) still shows the highest loss, probably due to larger strands and to difficulty in obtaining a smooth contour with this type of construction. The types D and E cables (curves 2 and 3) show almost identical loss although type D has appreciably larger strands. The type B cable (curve 4) was obtained from single phase measurements, which gives lower loss values; however, all the shift cannot be accounted for by this fact and may be attributed to the exceptionally smooth stranding and small wires in the outer layer. The type F conductor (curve 5) although showing a relatively low loss in the higher voltage range has a high loss in the low voltage or operating range. This probably is due to roughness of the individual segments and to the arched segment construction used. As was the case with the previously described condition, the type C conductor (curve 6) showed the lowest loss of any of the 1.4-in. conductors. No tests were available on the 1.65-in. type C conductor. Referring to curve 8 of Fig. 11 for the 1.65-in. type C conductor, it may be seen that it has practically the same loss as the 1.4-in. type C conductor after the latter had a second clear water rinse. The 1.4-in. conductor was manufactured in the United States and was a smoother job than the 1.65-in. conductor which was of foreign make.

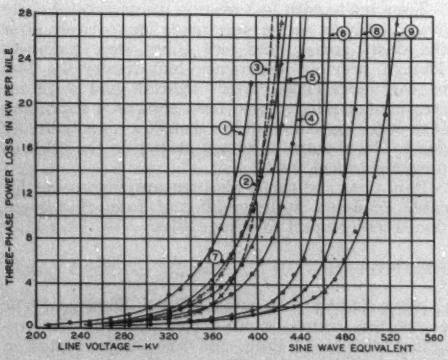


Fig. 12. Corona loss curves for all cables after gasoline, soap and water washing

Curve No.	Date	Cable	Barom. In. Hg	% Rel. Humid.	Temp. Deg F Air	Cable
1	4-3-33	Type A	29.78	53	71.5	82.0
2	5-16-33	Type B	29.95	62	59.5	62.0
3	7-11-33	Type D	29.75	26	93.0	102.0
4	8-3-33	Type E	29.92	52	71.0	
5	10-27-31	1.49-in. stranded copper	30.05	27	71.0	80.0
6	6-8-33	1.4-in. type C	29.91	25	76.0	88.0
7	8-18-33	Type F	29.73	57	73.0	84.0
8	9-7-33	1.65-in. type C	29.57	20	82.0	94.0
9	11-12-31	2-in. stranded aluminum	30.05	21	66.0	80.0

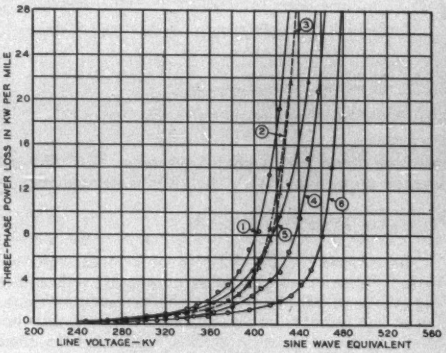


Fig. 13. Corona loss curves for all cables after clear water washing

Curve No.	Date	Cable	Barom. In. Hg	% Rel. Humid.	Temp. Deg F Air	Cable
1	4-12-33	Type A	29.99	31	73.0	86.0
2	7-27-33	Type D	29.63	31	86.0	100.0
3	8-16-33	Type E	29.77	36	90.0	100.0
4	5-31-33	Type B	29.83	40	65.5	70.0
5	8-29-33	Type F	29.81	48	73.0	82.0
6	6-23-33	1.4-in. type C	29.86	36	70.0	78.0

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Cross Potential of a 4-Arm Network

This paper treats the loci of potential difference across the midpoints of a 4-arm network with constant coefficients and constant applied voltage. When the network is operated at constant frequency and any one of its arms varies along one of its components or at constant phase angle, the locus of potential difference is a circle. When the network arms remain fixed and the frequency is varied, the locus may or may not be a single circle and in many instances may be expressed as the sum of 2 circles or a circle and a bicircular quartic. To illustrate the practical application of this work, the analytical treatment and numerical results are given for typical networks.

By
ANATOLI C. SELETZKY
ASSOCIATE A.I.E.E.
Case School of Applied Science, Cleveland, Ohio

INCREASING USE of bridge circuits, consisting chiefly of 4-arm networks, not only for measurements of electrical quantities, but also for control and recording purposes, calls for a more critical consideration of the performance of such circuits. In measurements of electrical quantities, where one or more of the bridge arms are varied until null voltage exists across the midpoints of the bridge, a frequent question that arises is the choice of the most appropriate type of circuit which will yield the greatest accuracy and sensitivity. When the choice of a bridge circuit has been narrowed to a single network, as determined by voltage requirements, current carrying capacity, available ranges of precision apparatus, type of null detector, and convenience and speed of manipulation, another problem still remains. This is the proportioning of the impedances of the network arms to obtain maximum sensitivity and accuracy. It is no longer sufficient merely to evaluate the conditions of the variable arm which produce null potential difference across the detector, but it is necessary to compute the currents flowing through the detector, or the potential difference across it if it draws no current, as the variable arm ranges through both sides of the balance point.

Computations of midpoint potential difference and detector currents have been avoided as much as possible because they invariably involve point-by-point calculation of several complex quantities comprising the analytical expression, in a none too convenient form. Obviously, when demands upon accuracy and sensitivity are not important the consideration of the unbalanced conditions may be omitted. However, when bridge networks are used for control and recording purposes, they may or may not be operated with null potential difference across the midpoints. Here, of course, the calculation of midpoint potential differences cannot be dispensed with.

This paper treats the variation of potential difference across the midpoints of a 4-arm network at both constant and variable frequencies. The results are obtained by considering the midpoint potential difference as one or more linear fractional transformations. The work necessary to determine the loci of the transformations, in general, entails less computation than the determination of 1 or 2 points in the usual point-by-point calculation. The treatment throughout is perfectly general and may be applied directly to the performance of any 4-arm network, the coefficients of which do not vary with frequency.. To illustrate the practical application of this work, the analytical treatment and the numerical results are given for typical networks when either the frequency or one of the arms is varied.

The results show that the locus of potential difference across the midpoints of a 4-arm network, with constant coefficients, operated at constant frequency and constant applied voltage is a single circle when (1) any one of the arms varies in magnitude at a constant phase angle; or (2) any one of the arms varies along one of its components. When the frequency is varied, the locus may or may not be a single circle. When the locus is not a single circle and no higher powers of frequency than the second occur in the expression for the potential, that expression may be broken down by partial fractions into the sum of 3 terms. In the most complicated case of this sort, these terms are a constant, a circle, and the square of a circle. The determination of loci by use of the Schenkel form of linear fractional transformation has been found to afford an accurate

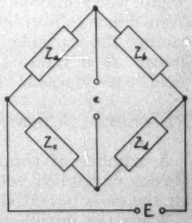


Fig. 1. General 4-arm network

Full text of a paper recommended for publication by the A.I.E.E. committee on instruments and measurements, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Sept. 22, 1933; released for publication Nov. 10, 1933. *Not published in pamphlet form.*

and rapid method of ascertaining the complete path of cross potential difference as a function of any variable desired.

General 4-Arm Network

In its most general form, the 4-arm network may be considered to be composed of 4 elements, having impedances, Z_a, Z_b, Z_c, and Z_d as shown in Fig. 1. If the applied voltage across the network be E, the cross potential difference, e existing across the midpoints, is

$$e = E\frac{Z_aZ_d - Z_bZ_c}{(Z_a + Z_b)(Z_c + Z_d)} \tag{1}$$

For most purposes it is more convenient to express the potential difference across the midpoints of the network in terms of volts per volt of applied voltage e',

$$e' = \frac{e}{E} = \frac{Z_aZ_d - Z_bZ_c}{(Z_a + Z_b)(Z_c + Z_d)} \tag{2}$$

Since this paper deals exclusively with the potential difference e' in terms of volts per volt of applied voltage, the author will take the liberty to refer to it as "cross potential," "midpoint potential," or merely "potential."

To treat the loci of the cross potential under various conditions, the equation of a circle will be used as originally applied to a-c circuits by Schenkel (*Elektrotechnische Zeitschrift*, v. 22, Dec. 19, 1901, p. 1043–4). For present purposes the canonical form of the circle will be

$$S = \frac{\alpha + \beta\rho}{\gamma + \delta\rho} \tag{3}$$

in which ρ is a scalar variable that may range from minus to plus infinity, and α, β, γ and δ are constants. Thus S is a variable vector emanating from the origin, whose extremity describes a circle as ρ ranges from minus to plus infinity. The form of eq 3, containing the variable ρ in the first degree only, is known as a linear fractional transformation and yields a circle when the variable is a scalar.

Networks at Constant Frequency

A number of conditions that, at constant frequency of applied voltage, give rise to circular loci for the cross potential now will be studied.

When the impedance of one of the arms, for example, Z_d, varies at constant phase angle, then Z_d may be written as $Z_d = Z_d'\rho$ where Z'_d is a unit vector having the same phase angle as Z_d, and ρ as before is the scalar variable. Then eq 2 may be expressed as

$$e' = \frac{-Z_bZ_c + Z_aZ_d'\rho}{(Z_a + Z_b)Z_c + (Z_a + Z_b)Z'_d\rho} \tag{4}$$

$$\left.\begin{aligned} \alpha &= -Z_bZ_c & \gamma &= (Z_a + Z_b)Z_c \\ \beta &= Z_aZ'_d & \delta &= (Z_a + Z_b)Z'_d \end{aligned}\right\} \tag{5}$$

Equation 4 is seen to be a circle in the form of a linear fractional transformation as given by eq 3; the corresponding constants are given in eqs 5.

When the resistive component of any one of the arms, as Z_d, varies, $R_d + jX_d = Z_d$ is substituted into eq 2, which gives

$$e' = \frac{-Z_bZ_c + jZ_aX_d + Z_aR_d}{(Z_a + Z_b)(Z_c + jX_d) + (Z_a + Z_b)R_d} \tag{6}$$

$$\left.\begin{aligned} \alpha &= -Z_bZ_c + jZ_aX_d \\ \beta &= Z_a \\ \gamma &= (Z_a + Z_b)(Z_c + jX_d) \\ \delta &= Z_a + Z_b \\ \rho &= R_d \end{aligned}\right\} \tag{7}$$

Similarly, when the quadrature component of any one of the arms, as Z_d, varies,

$$e' = \frac{-Z_bZ_c + Z_aR_d + jZ_aX_d}{(Z_a + Z_b)(Z_c + R_d) + j(Z_a + Z_b)X_d} \tag{8}$$

$$\left.\begin{aligned} \alpha &= -Z_bZ_c + Z_aR_d & \delta &= j(Z_a + Z_b) \\ \beta &= jZ_a & \rho &= X_d \\ \gamma &= (Z_a + Z_b)(Z_c + R_d) \end{aligned}\right\} \tag{9}$$

Both eqs 6 and 8 have circles for their loci since R_d and X_d are the respective scalar variables, the constants in each case being given by eqs 7 and 9.

Equations 4, 6, and 8 show that at constant frequency the cross potential of a 4-arm network follows a circular locus for either of the following conditions: (1) variation of impedance of any one of the arms at constant phase angle; (2) variation of either resistive or quadrature components in any one of the arms. The variable under either condition may vary over any part or all of the range from minus to plus infinity. The importance of eqs 4, 6, and 8 is that in lieu of a separate computation involving complex quantities for each value of the variable desired, a circle that includes all possible values of the variable may be determined very simply from the network constants. Another feature of equal significance is that a "scale line," that is, a straight line correlating directly the linear scale of

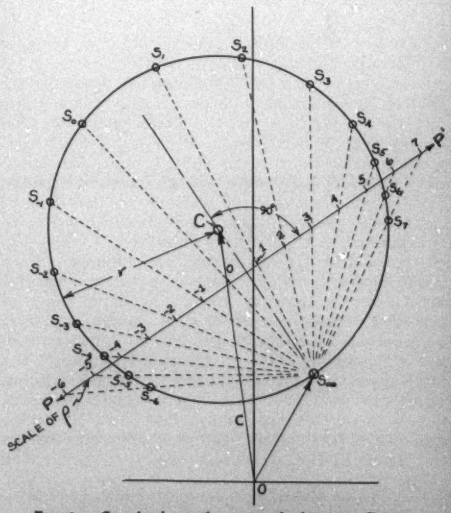
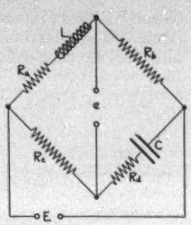


Fig. 2. Circular locus for network shown in Fig. 1, note relationship between the scale line and circle

Fig. 3. A typical 4-arm network



the variable arm with corresponding points on the circle, may be obtained readily by utilizing an invariant point of the transformation.

Of the various methods available for determining the radius and the center of the circle, 2 will be described. (See W. O. Schumann, "Zur Theorie der Kreisdiagramme," *Arch. f. Elektrot.*, v. 11, July 28, 1922, p. 140–6.) The first method, analytical in character, follows directly from the equations necessary to demonstrate that the form of eq 3 is circular. From these equations it has been shown that the radius r and the center vector c (the vector joining the center of the circle with the origin) are:

$$r = \left| \frac{\alpha\delta - \beta\gamma}{\delta\gamma_c - \gamma\delta_c} \right| \tag{10}$$

$$c = \frac{\alpha\delta_c - \beta\gamma_c}{\gamma\delta_c - \delta\gamma_c} \tag{11}$$

in which the subscript c indicates the conjugate of the vector to which it is attached. Thus the determination of the position of the center and the radius of the circle involves merely straightforward substitution in the foregoing formulas.

The second method of locating the circle is the determination of the center point and the radius from 3 different values of the variable scalar ρ. The ease of this procedure lies in the fact that the values of the variable may be so chosen as to reduce eq 3 to much simpler forms. For instance, when $\rho = 0$

$$S_0 = \frac{\alpha}{\gamma} \tag{12}$$

and when $\rho = \infty$

$$S_\infty = \frac{\beta}{\delta} \tag{13}$$

The third point is obtained by taking some other value of ρ, which likewise in many instances can be so chosen as to simplify the resultant expression.

The scale line for the circle is any line drawn perpendicularly to the line joining the center of the circle and the point on the circle corresponding to $\rho = \infty$. The intersections of the scale line, drawn in this manner, with lines joining points on the circle at which ρ is known and the point at which $\rho = \infty$, determine a linear scale of ρ on the scale line. Any line drawn from the point on the circle at which $\rho = \infty$ to the scale line and intersecting the circle, connects corresponding values of ρ on the scale line and on the circle.

The relationship between the scale line and the circle is illustrated in Fig. 2. Here the scale line is represented by PP', drawn perpendicularly to the line CS_∞. Lines drawn from S_∞ to any points on the circle, such as S_0 and S_1, fix the scale on the scale line. The scale then is extended linearly along PP'. Then any vector, such as OS_8, represents the value of S in magnitude and phase for $\rho = 5$, since the line joining S_∞ and S_8 cuts the scale line at $\rho = 5$.

These methods of drawing circular loci will now be applied to a resistance, inductance, and capacitance network, as shown in Fig. 3. The cross potential will be evaluated as a function of the capacitance C. The constants of this network are

$$Z_a = R_a + j\omega L \qquad Z_c = R_c$$
$$Z_b = R_b \qquad Z_d = R_d - \frac{j}{\omega c}$$

Inserting these constants into eq 2, the midpotential becomes

$$e' = \frac{(R_a + j\omega L)\left(R_d - \frac{j}{\omega c}\right) - R_b R_c}{(R_a + R_b + j\omega L)\left(R_c + R_d - \frac{j}{\omega c}\right)} \tag{14}$$

Since C is now the scalar variable representing ρ in eq 3, the expression for potential in eq 14 must be reduced to an appropriate circular form with C as a factor of a single term in the numerator and the denominator. Rearranging the terms in eq 14 accordingly gives

$$e' = \frac{R_a + j\omega L}{R_a + R_b + j\omega L} \times \frac{-j + C\omega\left(Rd - \frac{R_b R_c}{R_a + j\omega L}\right)}{-j + C\omega\,(R_c + R_d)} \tag{15}$$

Equation 15 is now a circle S in canonical form, multiplied by a factor that has been taken out to simplify the component terms of the circle which are:

$$\left.\begin{aligned} \alpha &= -j & \gamma &= -j \\ \beta &= \omega\left(R_d - \frac{R_b R_c}{R_a + j\omega L}\right) & \delta &= \omega(R_c + R_d) \\ & & \rho &= C \end{aligned}\right\} \tag{16}$$

Then the cross potential is

$$e' = \frac{R_a + j\omega L}{R_a + R_b + j\omega L} \times S \tag{17}$$

Thus the locus of e' is obtained by multiplying the scale of S by the absolute value of $\frac{R_a + j\omega L}{R_a + R_b + j\omega L}$ and rotating the axes through an angle equal and opposite to the phase angle of the same factor.

Substituting the various terms of eq 16 in eqs 10 and 11, the radius of S becomes

$$r = \left| \frac{-R_c}{2(R_c + R_d)} \left[1 + \frac{R_b}{R_a + j\omega L} \right] \right| \tag{18}$$

and the center vector

$$c = \frac{1}{2(R_c + R_d)} \left[R_c + 2R_d - \frac{R_b R_c}{R_a + j\omega L} \right] \tag{19}$$

The evaluation of r and c allows the circle to be drawn in its correct position. To locate the scale line S must be evaluated for 2 points. Likewise S could be calculated for a third point to give 3 points for the determination of the circle without recourse to eqs 18 and 19 for the radius and the center vector. Thus when $C = 0$, $S_0 = 1$, and when $C = \infty$

$$S_\infty = \frac{1}{R_c + R_d} \left[R_d - \frac{R_b R_c}{R_a + j\omega L} \right]$$

It will become apparent from the numerical example

that follows, that the value of C for the third point may be so chosen as to render the calculation of S for that point quite simple. In fact, if R_d has an appropriate value, so that the locus of e' passes through the origin, then that value of C for which S is zero may be used conveniently.

These results now will be applied to a numerical example. Suppose that it is desired to operate the network at 1,000 cycles per second and to have null potential across the midpoints for a particular value of the capacitance arm. The conditions for null cross potential for this network are

$$\left.\begin{aligned} R_d &= \frac{R_a R_b R_c}{R_a^2 + \omega^2 L^2} \\ C &= \frac{R_a^2 + \omega^2 L^2}{R_b R_c \omega^2 L} \end{aligned}\right\} \qquad (20)$$

The following constants will be employed:

$L = 0.2870$ h
$R_a = 1{,}130$ ohms
$R_b = R_c = 2{,}000$ ohms
$R_d = 1{,}000$ ohms

The locus of e' now will be determined as C varies from zero to infinity. From eqs 20 the potential across the midpoints will be zero when $R_d = 1{,}000$ ohms and $C = 10^{-7}$ farad. Using these constants,

When $C = 0$, $S_0 = 1$
When $C = 10^{-7}$, $S = 0$
When $C = \infty$,

$$S = \frac{1{,}000 - \dfrac{2{,}000 \times 2{,}000}{1{,}130 + j2\pi \times 1{,}000 \times 0.2870}}{2{,}000 + 1{,}000} = j\,0.5305$$

These 3 values of S now may be used to determine the circle. The position of the center and the radius also may be checked by eqs 18 and 19 which give:

$$r = \left|\frac{-2{,}000}{2(2{,}000 + 1{,}000)}\left[1 + \frac{2{,}000}{1{,}130 + j2\pi \times 1{,}000 \times 0.2870}\right]\right| = 0.5658$$

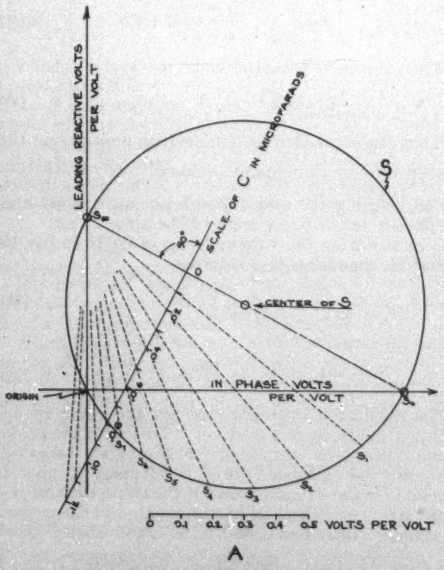
$$c = \frac{2{,}000 + 2{,}000 - \dfrac{2{,}000 \times 2{,}000}{1{,}130 + j2\pi \times 1{,}000 \times 0.2870}}{2(2{,}000 + 1{,}000)} = 0.5003 + j\,0.2654$$

The resultant locus for S is shown in Fig. 4A. To obtain the locus for e', S must be multiplied by $\dfrac{R_a + j\omega L}{R_a + R_b + j\omega L} = 0.5891/\underline{29.94}°$ as shown in Fig. 4B. The scale line then is drawn as previously described, using the points on S for $C = 10^{-7}$ and $C = 0$. The value of cross potential for any value of C now may be read directly on Fig. 4B. Variation of the magnitude and phase of the cross potential with capacitance is shown in Fig. 5.

Any type of 4-arm network with constant coefficients, in which one arm varies at constant phase angle or along one of its components, may be treated exactly as in the foregoing example.

Networks at Variable Frequency

The expression for the cross potential of a 4-arm network when all the arms remain fixed and the frequency is varied, in many cases does not yield a single circular locus. It is necessary in each in-



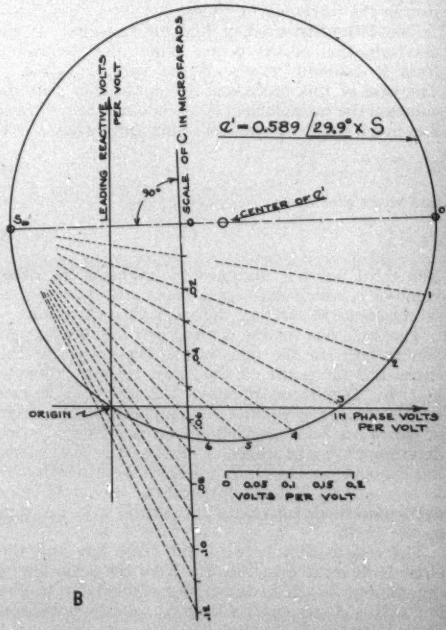

e' = 0.589 /29.9° x S
LEADING REACTIVE VOLTS PER VOLT
SCALE OF C IN MICROFARADS
CENTER OF e'
ORIGIN
IN PHASE VOLTS PER VOLT
0 0.05 0.1 0.15 0.2 VOLTS PER VOLT
B

Fig. 4. Circular loci for circuit shown in Fig. 3 showing variation of e' with C, at constant frequency

stance to set up the equation for e' in terms of the particular impedances at hand and then to rearrange the terms with respect to ω with a view of reducing the expression to the canonical form of the circle in eq 3. When only first powers of ω occur, the entire process is exactly similar to the problem first studied, namely, the determination of e' as a function of one of the network arms, with the exception that the frequency is treated as the scalar variable. However, when second or possibly higher powers of ω occur in the equation for e', it is possible to resolve e' into a sum of linear fractional transformations having circles for their loci. This particular method was developed by Hauffe (G. Hauffe, "Zur Theorie der Allgemeinen Ortskurven," *Elektrot. u. Masch.-Bau*, v. 48, Jan. 19, 1930, p. 57–8) for the determination of loci of the simple series circuit, but, as will be shown here, the same treatment is readily applicable to the 4-arm network.

Let it be assumed that the constants of the network are such that no powers higher than the second enter into the equation for the cross potential. Then the expression for e' may be written as

$$e' = \frac{A\omega^2 + B\omega + C}{\omega^2 + D\omega + E} \tag{21}$$

in which A, B, C, D, and E are constants. Let the denominator be solved as a quadratic in ω, giving, say, 2 different roots ω_1 and ω_2, which may be real or complex. The case involving equal roots will be treated later.

Unequal Roots. Using partial fractions the cross potential is put into the form

$$e' = \frac{A\omega^2 + B\omega + C}{\omega^2 + D\omega + E} = M_1 + \frac{M_2}{\omega - \omega_1} + \frac{M_3}{\omega - \omega_2} \tag{22}$$

in which M_1, M_2, and M_3 are constant terms free of ω. Equating coefficients gives: $M_1 = A$, and M_2 and M_3 in terms of A, B, C, ω_1, and ω_2. Since both of the last 2 terms of eq 22 contain only first powers of ω, each may be reduced to a linear fractional transformation having a circle for a locus. Thus

$$e' = A + S_2 + S_3 \tag{23}$$

in which

$$S_2 = \frac{M_2}{\omega - \omega_1} \text{ and } S_3 = \frac{M_3}{\omega - \omega_2}$$

The potential existing across the network is seen now to be equal to a constant added to 2 circular loci. Equation 21 is a special form of the general fractional transformation of degree n, where n is 2, and is known as a bicircular quartic.

As an example of this type of problem, consider the same network as before, the various arms remaining fixed and the frequency varying from zero to infinity. Rearranging eq 14 according to descending powers of ω we have

$$e' = \frac{\frac{1}{R_c + R_d}\left\{\omega^2 R_d - \frac{j\omega}{CL}\left[L + C(R_c R_d - R_b R_c)\right] - \frac{R_a}{CL}\right\}}{\omega^2 - \frac{j\omega[L + C(R_a + R_b)(R_c + R_d)]}{CL(R_c + R_d)} - \frac{R_a + R_b}{CL(R_c + R_d)}} \tag{24}$$

This equation is not a circle, considering ω as the variable, since it cannot be reduced to the form of eq 3. If, however, the denominator of eq 24 be

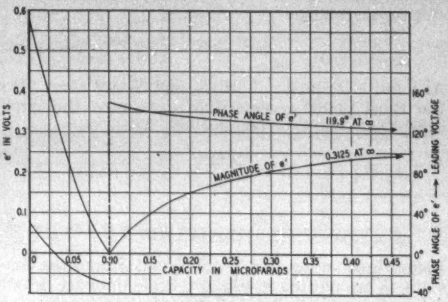


Fig. 5. Variation of cross potential with capacitance for a circuit as shown in Fig. 3 having the following constants:

L = 0.2870 h
R_a = 1,130 ohms
$R_b = R_c$ = 2,000 ohms
R_d = 1,000 ohms

solved as a quadratic in ω, the entire expression will break down into the sum of a constant term and 2 circular loci as described. If the 2 roots of the denominator are not equal, they are

$$\omega_1 = \frac{j}{C(R_c + R_d)} \text{ and } \omega_2 = j\frac{(R_a + R_b)}{L}$$

The cross potential then may be expressed as

$$\frac{\frac{1}{R_c + R_d}\left\{\omega^2 R_d - \frac{j\omega[L + C(R_a R_d - R_b R_c)]}{CL} - \frac{R_a}{CL}\right\}}{\omega^2 - \frac{j\omega[L + C(R_a + R_b)(R_c + R_d)]}{CL(R_c + R_d)} - \frac{R_a + R_b}{CL(R_c + R_d)}} = M_1 + \frac{M_2}{\omega - \omega_1} + \frac{M_3}{\omega - \omega_2} \tag{25}$$

Equating coefficients of like powers of ω,

$$M_1 = \frac{R_d}{R_c + R_d};\ M_2 = \frac{-jR_c}{C(R_c + R_d)^2};\ M_3 = \frac{jR_b}{L}$$

Substituting for M_1, M_2, M_3, ω_1, and ω_2 in eq 25, the cross potential assumes the form

$$e' = \frac{R_d}{R_c + R_d} - \frac{jR_c}{(R_c + R_d)[\omega C(R_c + R_d) - j]} + \frac{jR_b}{\omega L - j(R_a + R_b)} \tag{26}$$

Thus the cross potential

$$e' = S_1 + S_2 + S_3$$

in which

$$S_1 = \frac{R_d}{R_c + R_d};\ S_2 = \frac{-jR_c}{(R_c + R_d)[\omega C(R_c + R_d) - j]};$$

$$S_3 = \frac{jR_b}{\omega L - j(R_a + R_b)}$$

When $\omega = \infty$, $S_2 = S_3 = 0$

When $\omega = 0$, $S_2 = \frac{R_c}{R_c + R_d}$ and $S_3 = \frac{-Rb}{R_a + R_b}$

For a numerical example, the same constants will be used as in the preceding example, maintaining C at 10^{-7} farad, which gives null cross potential at 1,000 cycles. Substituting these constants

$$S_1 = \frac{1{,}000}{2{,}000 + 1{,}000} = 0.3333$$

For zero frequency

$$S_2 = \frac{2{,}000}{2{,}000 + 1{,}000} = 0.6667 \text{ and } S_3 = \frac{-2{,}000}{1{,}130 + 2{,}000} = -0.6389$$

At infinite frequency both S_2 and S_3 are zero. For the third point necessary to determine the circle take, for example, 1,000 cycles. Then

$$S_2 = \frac{-j\,2{,}000}{(2{,}000 + 1{,}000)\,[2\pi \times 1{,}000 \times 10^{-7}\,(2{,}000 + 1{,}000) - j]} = 0.3124\ \underline{/-62.05°}$$

$$S_3 = \frac{j\,2{,}000}{2\pi \times 1{,}000 \times 0.2870 - j\,(1{,}130 + 2{,}000)} = 0.5536\ \underline{/150.06°}$$

Using these values, the 2 loci S_2 and S_3 and the constant S_1 are plotted in Fig. 6. Scale lines are drawn for each of the circles and corresponding points on each circle are added together with the constant, giving the resultant cross potential across the network.

Double Root. When the roots of the denominator are equal, the general quadratic form is written as the sum of several fractions, as before.

$$e' = \frac{A\omega^2 + B\omega + C}{\omega^2 + D\omega + E} = M_1 + \frac{M_2}{\omega - \omega_0} + \frac{M_3}{(\omega - \omega_0)^2} \qquad (27)$$

Here the root is ω_0. The first term on the right is a constant, equal to A, and the second term is a circle, as in the preceding example. If the third term be considered as the square of its square root, it then can be treated as the square of a circular locus, because the square root of the third term is a circle. Thus

$$e' = S_1 + S_2 + S_3^2 \qquad (28)$$

in which

$$S_1 = A;\ S_2 = \frac{M_2}{\omega - \omega_0};\ S_3 = \frac{\sqrt{M_3}}{\omega - \omega_0}$$

When the locus of S_3 has been determined, a number of points on it are squared, giving the bicircular quartic, S_3^2. The locus of S_3^2 then is added to $(S_1 + S_2)$ thereby giving the desired locus of e'.

If the conditions for a double root be applied to the preceding problem, the coefficient M_3 will be found to be zero. Thus in this particular case the locus of the cross potential is a constant added to a single circle, the point S_2 for zero frequency being coincident with the point S_2 for infinite frequency. To illustrate the problem involving a double root, the network in Fig. 7 will be employed. It should be observed that with an inductance in the (a) arm, a capacitance in the (b) arm and resistances only in the remaining arms, the locus of the cross potential will not pass through the origin at any frequency.

Referring to eq 2 the cross potential for this network becomes

$$e' = \frac{(R_a + j\omega L)\,R_d + j\,\frac{R_c}{\omega C}}{\left[R_a + j\left(\omega L - \frac{1}{\omega C}\right)\right]\left[R_c + R_d\right]} \qquad (29)$$

If all the resistances in the various arms are made alike and the equation rearranged according to descending powers of ω,

$$e' = \frac{1}{2} \times \frac{\omega^2 + j\,\frac{R}{L}\,\omega + \frac{1}{LC}}{\omega^2 - j\,\frac{R}{L}\,\omega - \frac{1}{LC}} \qquad (30)$$

Considering the denominator as a quadratic in ω, the roots will be equal when $L = \frac{CR^2}{4}$, and the double root, ω_0 is $j\,\frac{2}{CR}$. The cross potential then may be written as

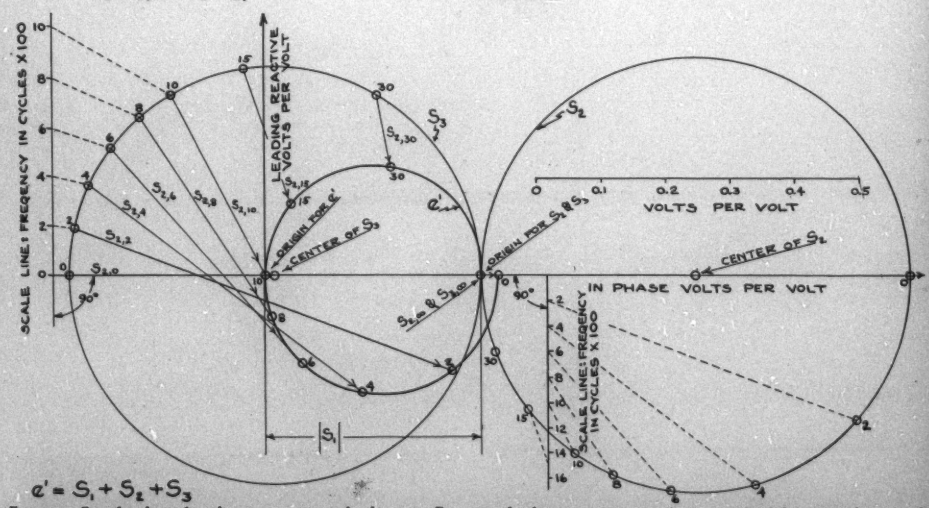


Fig. 6. Circular loci for the 4-arm network shown in Fig. 3 as the frequency is varied; constants of the network are such that the equation for cross potential contains no powers of ω higher than the second and the denominator has unequal roots

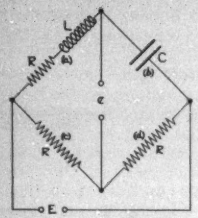


Fig. 7. A typical 4-arm network used to illustrate problem of variable frequency in which denominator of equation for cross potential has equal roots

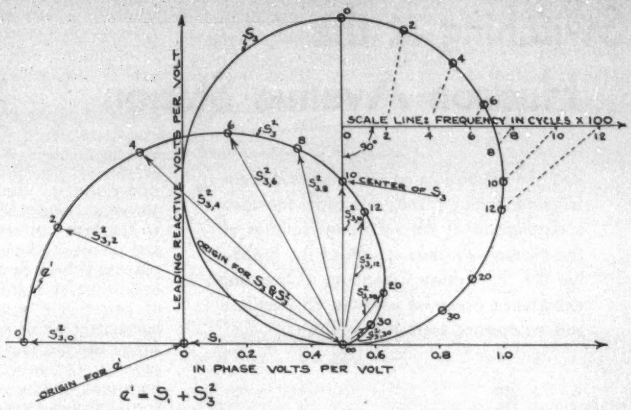

LEADING REACTIVE VOLTS PER VOLT
SCALE LINE: FREQUENCY IN CYCLES X 100
CENTER OF S_3
ORIGIN FOR S_3 & S_3^2
ORIGIN FOR e'
IN PHASE VOLTS PER VOLT
$e' = S_1 + S_3^2$

Fig. 8 (right). Loci for circuit shown in Fig. 7

$$\frac{1}{2} \times \frac{\omega^2 - j\frac{R}{L}\omega + \frac{1}{LC}}{\omega^2 - j\frac{R}{L}\omega - \frac{1}{LC}} = M_1 + \frac{M_2}{\omega - \omega_0} + \frac{M_3}{(\omega - \omega_0)^2} \qquad (31)$$

Equating coefficients

$$M_1 = \frac{1}{2};\ M_2 = 0;\ M_3 = \frac{4}{C^2R^2} = \omega_r^2$$

Here, $\omega_r = \frac{1}{\sqrt{LC}}$, the angular velocity at which the reactances of the inductance and the capacitance are equal. Substituting these coefficients in eq 31 and noting that $\omega_0 = j\omega_r$ the cross potential becomes

$$e' = \frac{1}{2} + \left[\frac{\omega_r}{\omega - j\omega_r}\right]^2 \qquad (32)$$

In this case the circle S_2 in eq 28 vanishes and the potential is composed of a constant term added to the square of a circular locus, that is $e' = S_1 + S_3^2$ in which

$$S_1 = \frac{1}{2} \text{ and } S_3 = \frac{\omega_r}{\omega - j\omega_r}$$

The critical points for S are:

for $\omega = \infty$, $S_3 = 0$
for $\omega = 0$, $S_3 = j$

for $\omega = \omega_r$, $S_3 = \frac{1+j}{2} = \frac{\sqrt{2}}{2}\underline{/45°}$

It is interesting to observe that the conditions for a double root coupled with equal resistances exercise such constraints upon the relationships among the network constants, that only one independent quantity ω_r appears in the expressions for the 3 points necessary to determine S_3. The term S_1 is also free of the network constants for the above conditions. Thus a plot of the locus of $(S_1 + S_3^2)$ may be employed for any combination of constants that satisfies the equation

$$R^2 = \frac{4L}{C} \qquad (33)$$

Referring to eq 11 for the center vector, the center vector of S_3 is

$$c = \frac{\omega_r}{-j\omega_r - j\omega_r} = \frac{j}{2}$$

Since the point for infinite frequency is at the origin and the point for zero frequency is at j and the center is at $j/2$, the circle is disposed symmetrically about the vertical axis. Furthermore from the value at $\omega = \omega_r$ of $S_3 = \frac{\sqrt{2}}{2}\underline{/45°}$ it may be seen that a line drawn at an angle of 45° in the first quadrant will intersect the circle at a point corresponding to a frequency at which $\omega = 1/\sqrt{LC}$. Hence a circle drawn through these points will be valid for any set of constants satisfying eq 33. It only remains to subdivide the scale line from $\omega = 0$ to $\omega = \omega_r$ into suitable divisions.

For example if for a network in which

$C = 10^{-6}$ farad
$L = 0.02533$ h
$R = 2\sqrt{\frac{L}{C}} = 318.4$ ohms

the circle be drawn as described, then the 45° line in the first quadrant will intersect the circle at a point corresponding to

$$\omega = \frac{1}{\sqrt{0.02533 \times 10^{-6}}} = 6{,}283 \text{ or } 1{,}000 \text{ cycles}$$

The locus of S_3 is drawn in Fig. 8. A few points on S_3, sufficient to give a smooth curve, are squared yielding S_3^2 as shown. The origin then is displaced by the vector S_1 and the locus of the cross potential is complete. This locus describes a path similar to the locus of potential obtained by Hauffe (*loc. cit.*) for the potential across an inductance coil connected in series with a condenser.

The treatment of cross current, that is, the currents that would flow through an impedance connected across the midpoints, involves a study of the 5-arm network. In numerous instances the cross current may be evaluated exactly as has been described for the cross potential in this paper. However, because of the addition of the fifth arm, the general case is more complicated. The author hopes to treat the 5-arm network in a future paper.

Switching at the Hudson Avenue Station

By
C. M. GILT
MEMBER A.I.E.E.

Brooklyn Edison Co.,
Brooklyn, N. Y.

Part of a symposium on switching at modern large generating plants, this paper includes a description of the switching facilities at the Hudson Avenue station of the Brooklyn (N. Y.) Edison Company. Operating experience obtained with the connections and equipment used also is given.

SWITCHING facilities at the Hudson Avenue generating station of the Brooklyn (N. Y.) Edison Company had to be adapted to meet the particular requirements of a large generating station serving a metropolitan area having a load center close to the generating station. The exacting requirements of maximum reliability of service and the high cost of land available had a strong influence on the selection of the equipment and schemes to be used.

The load conditions which affected the design of the Hudson Avenue station are described in this paper, and the fundamental scheme of connections which was adopted is described. The physical design of the switching facilities and the actual equipment adopted is outlined, and those features which distinguish this plant from other large generating stations are pointed out. The control and relaying scheme used is described. The operating experience actually obtained at this station also is described in the paper, this experience covering the scheme of connections used, the equipment adopted, and the control and relay schemes used. Improvements which are now available and which might be used in future installations also are indicated.

Load Conditions Affecting Design

The Brooklyn Edison Company serves the borough of Brooklyn, N. Y., having a total area of approximately 80 sq miles, a net area served of 51 sq miles, a population of approximately 2,600,000, and a total coincident load of 323,000 kw. The load is largely residential, commercial, and small power, with no manufacturers using large, concentrated blocks of power such as are found in many heavy industrial areas. The load is fairly well diversified throughout most parts of the city, with the heaviest loads in the manufacturing and shipping areas along the waterfront and in the downtown Fulton Street area. All transmission above 5,000 volts must be underground. Such conditions, and the fact that the generating station is located in the city and close to the load centers, placed upon the station switching many of the requirements of a substation and precluded bulk power transmission. The life hazard and other hazards resulting from an extensive outage of power in a community containing such extreme concentration of population of heterogeneous characteristics put maximum continuity of service uppermost in the minds of the station designers. The high cost of land and foundations made a concentrated design essential.

In 1922, when the Hudson Avenue Station was planned, the total load amounted to 140,000 kw, of which approximately one third was at 60 cycles, the remainder being either direct current or at 25 cycles. The rapidity with which load was growing, about 14 per cent a year, and the inadequacy of the existing equipment made possible a combined new design of generating station and distribution system and the conversion of the old 2-phase substations and lines to the new 3-phase system.

There was a 60-cycle station of 63,000-kw capacity and a 25-cycle station of 125,000-kw capacity. Ties were provided between Hudson Avenue and this old 60-cycle station, and a 35,000-kw frequency converter provided an interconnection to the 25-cycle station. While it was believed that the general development of power supply in the metropolitan area would lead to interconnections with other stations, the new Hudson Avenue Station was designed to be the principal source of supply for the borough of Brooklyn, carrying as much of the 25-cycle load as could be done economically and safely, as well as the bulk of the 60-cycle load, without significant interconnections to other companies. The station was planned for 8 50,000-kw units and auto transformers, with all switching at 27,600 volts. When completed, the 8 units installed totaled 770,000 kw.

One-Line Diagram

The switching arrangement (see Fig. 1) is so closely related to the distribution system plan that the latter must be outlined briefy. The 60-cycle system was designed to be supplied from substations, each provided with 3 or more 10,000-kva transformers supplied by similarly rated cables from Hudson Avenue, without high voltage switching at the substation, and with a spare transformer energized from a cable ring interconnecting the various substations, switched at each station and supplied at one or more points by cables to Hudson Avenue. The 4,000-volt substation busses were sectionalized by circuit breakers and reactors, and the 27,000-volt

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feeders were carried over different routes and supplied from separated busses at the generating station so that the simultaneous outage of 2 supplies to a substation could be practically relegated to the rare coincident but unrelated outages of 2 feeders. Such second contingency conditions could be met if necessary by temporary 4,000-volt feeder reconnections. Later, direct supply to a low-voltage a-c network was developed and the same principle of diversified feeds was carried out.

In view of the fact that each substation was always provided with sufficient feeders and transformers to carry its load at any time with one feeder out, and that cable repairs or changes take so long that ordinary circuit breaker maintenance can be done while the feeder is out for other purposes, it was believed that one feeder breaker per feeder at the generating station was all that would be required and the costs, complications, and hazards of the second breaker could be eliminated. As a means of providing a back-up protection in case of feeder breaker failure and as a means of selecting between at least 2 sources of power, 4 feeder breakers were connected to a small group bus which could be tied to either of 2 generators through 1 of 2 automatic selector breakers. As originally planned, 2 groups of 4 feeders each, totaling 80,000 kva in feeder capacity, were allocated to each 62,500-kva generator. As the size of the units grew, the increased outlet capacity was obtained by increasing the cable size from 350,000 to 500,000 cir mils and by connecting 2 feeders to

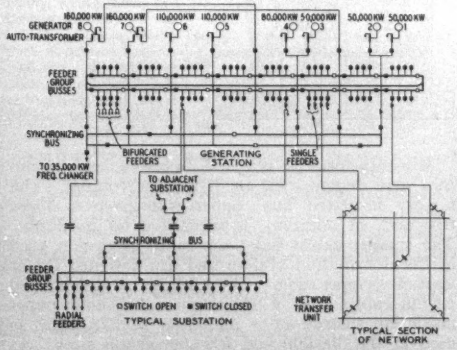

Fig. 1. One-line diagram of 27-kv bus connections at Hudson Avenue station, and typical system connections for supply to substations and to network

Note diversity of supply to typical substation and section of the network. Ties to Hell Gate station are distributed among the feeder busses. The diagram shows the bus connections for all units operating

1 feeder switch through non-automatic oil-immersed disconnecting switches.

While the object was sought of keeping bus sections small with thorough segregation to minimize the effect of station failures, yet some tie capacity between sections was considered important, first to avoid the necessity of tying busses together and operating in few large sections when the number of units was small; second, to provide for load transfer within the station so that units might be operated

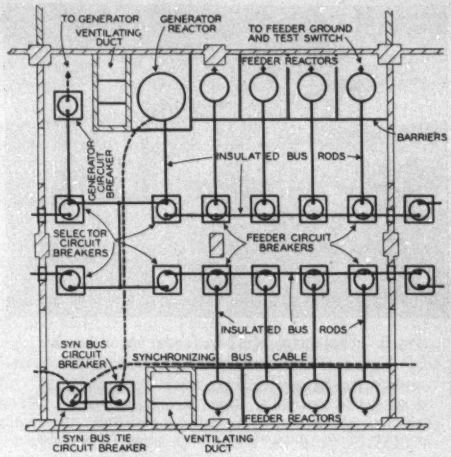

Fig. 2. Plan of typical section of switch gallery

Each section of 8 feeder reactors, circuit breakers, and associated bus and generator breakers is in a separate, fireproof room

for best economy without excessive unbalance of load and voltage on feeders; and, third, to provide a back-up supply of energy to all feeders so that the loss of a unit would have the minimum effect on any load. This was accomplished by connecting the generator busses through 10 per cent reactors and circuit breakers to a tie bus or "synchronizing bus" as it has been called. The synchronizing bus was built in the form of a ring and was provided with automatic sectionalizing breakers between each connection from a generator, so as to minimize the effect of a failure. The complete bus scheme is of the star design rather than the completely isolated or ring bus design. There are various advantages and disadvantages of the star bus as compared with the ring bus design, but probably the controlling factors in the selection of the star bus were the somewhat greater facility of maintaining small bus sections regardless of the number of units running, perhaps a little simpler relaying, and the fact that inherently there are at least 2 breakers between every feeder bus section so that the failure of any breaker will not affect more than one feeder bus section.

Some changes in connections were made necessary due to the fact that the station was planned for 8 50,000-kw turbines, but when completed there were installed 3 50,000-kw, 1 80,000-kw, 2 110,000-kw, and 2 160,000-kw units. These changes consisted essentially in reconnecting the 4 smallest machines

into 2 groups of 2 units each, making use of the double-winding principle in the autotransformers of the 2 largest units and connecting one half of each of these units in the positions originally assigned to them and the other half in the positions released by

Fig. 3. Photograph of 27-kv feeder circuit breaker installation

All 27-kv automatic breakers are of the disconnecting type supported on steel frames. Busses are insulated and barriers surround the disconnecting devices of the breakers. Doors between fireproof rooms were opened for taking of photograph

the transfer of connections of the second and fourth units. As compared to single winding units connected as originally planned this arrangement reduced the maximum short-circuit currents, made the generating capacity on each bus section more nearly uniform, and so distributed the connections of the 2 most economical machines among the busses that switching arrangements could be made under various conditions of load to permit their carrying their proper load with a minimum transfer through the synchronizing bus and reactors. The number of synchronizing bus sections was reduced to provide the additional generator breaker positions. In Fig. 1 is indicated the bus arrangements and typical connections to a substation, and a small section of the network. Obviously, some bus, breaker, and reactor current-carrying capacities had to be increased.

Physical Design and Equipment

In the endeavor to reduce the likelihood of accidental contact and failure, and to limit the extent of the failure should one occur, exposed live parts were eliminated as far as practicable. This seemed particularly desirable in view of the fact that the operating voltage is 27,600 volts, each generator feeding directly into a bank of Y-Y connected autotransformers with neutrals solidly grounded without any intervening switching. The synchronizing bus consists of lead covered cable, looped from one circuit breaker to the next, terminating at each end in a pothead forming part of the stationary contact of the circuit breaker. The busses connecting the generator switches, selectors, feeder switches, and reactors consist of short sections of factory insulated copper rod or tubing with taped joints supported on 37,000-volt insulators. The insulation is of the "herkolite" or "micarta" type. The same material is used to form shields which surround the bushings and disconnecting contacts of the elevating-type circuit breakers. The early feeder and "generator" reactors were of the bare copper concrete type but the later ones have all been provided with turn insulation. These are completely separated from the rest of the circuit breaker room by asbestos board barriers, except for small, screened ventilating openings, and asbestos board partitions are between the reactors.

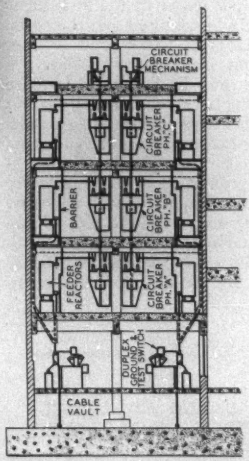

Fig. 4. Cross section of 27-kv switch gallery

The switch gallery is built on the vertical isolated phase principle. Cables are lead covered in ducts imbedded in concrete. Phase isolation is maintained from generator to ground and test switches

Autotransformers, reactors, breakers, and insulators were designed for an 81-kv test voltage. The factory insulated bus copper was given a 58-kv test and, in addition, is supported on insulators. The smaller cables have the same insulation used in the distribution system and are designed for at least 29-kv operation. The 1,500,000 and 2,000,000 cir-mil cables have a minimum of 375 mills paper insulation instead of a minimum of 328 mills as used in the 350,000 and 500,000 cir-mil sizes. As in the street work, insulation thickness has been somewhat decreased as improved cable became available.

The switch house is built on the vertical isolated phase principle with each generator switch and its associated selectors, breakers, synchronizing bus breakers, 2 groups of feeder breakers and reactors in a separate room with swinging, fireproof doors between rooms. In Fig. 2 is indicated the physical arrangement of one of these rooms, and a view inside these rooms is reproduced in Fig. 3. A cross section of the 27-kv switch gallery is shown in Fig. 4, and the feeder reactor installation is illustrated in Fig. 5. Ventilation is secured by ducts rising from the

ground floor, discharging under the reactors, picking up again above the reactors and discharging above the roof. There is a separate air duct for each phase of each group of reactors. Small screened openings top and bottom in the reactor barriers permit some air to by-pass through the open portion of the room.

The circuit breakers are of the General Electric *K*-130 elevating type, of 600, 1,200, 2,000, and 3,000-amp capacities. The 600-amp feeder breakers have an interrupting rating of 500,000 kva and are of the plain break construction, while all others are rated 1,500,000 kva and are equipped with explosion chambers. In Table I are shown the breaker ratings and the duties that may be imposed on them in actual operation. The breakers are supported on steel frames hung from the building steel, the frames for all breakers being of the same dimensions, so that breakers of all ratings are interchangeable. Screw shafts operated from the mechanisms on the floor above the top breakers raise and lower the breakers between the operating and disconnect positions and also still further lower the tanks for maintaining oil and breaker parts. There are no

Table I—Oil Circuit Breaker Current Carrying and Interrupting Ratings and Duties, Hudson Avenue Station

Circuit Breaker	Amperes			Thousands of Kva		
		Current Duty		Interrupting	Interrupting Duty[5]	
	Current Rating	Original Plan	Present	Rating 2-0C0 Cycle	Original Plan[6]	Present[7] Equipment
Feeder	600[1]	300	600	500	250	430[3]
Feeder	1,200		825	1,500		1,600[3]
Selector	1,200	1,200	1,200	1,500	850	1,500
Selector	2,000		2,000	1,500		1,700
Generator	2,000	1,310	1,310	1,500	500	1,050
Generator	3,000		2,880	1,500		975
Syn. Bus	3,000	2,400[4]	3,000	1,500	1,600	1,600
Syn. Bus Tie	3,000	2,400	3,000	1,500	1,600	1,600

1. Contacts rated 600-amp were the smallest advisable for 500,000-kva breakers
2. The increased duty on feeder breakers is due largely to larger feeder reactors having less impedance than original 300-amp reactors
3. Due to short time settings for certain tie feeders permitting feeder breakers to interrupt faults in feeder reactors
4. Two feeder groups of 1,200 amp each
5. Basis of calculation: All generators running at full rated load; all ties with other stations connected; decrement of fault current taken into account
6. As if for 8 50,000-kw generators, with all synchronizing bus switches closed
7. Maximum duties for station as actually completed, with generators totaling 770,000 kw, and with the synchronizing bus operated in 2 sections. Substantial reduction of these duties can be accomplished by further sectionalizing the synchronizing bus, and reduction also does accompany the normal operating condition with less than full rated load on the station

barriers between breakers within a building section as it was believed that the proximity of ample grounded steel would confine an arc to a short local path, and the practical elimination of exposed live parts would prevent the flashover of other circuits due to ionized gases. The whole construction preceded the introduction of metal-clad switch gear into this country, but is quite similar to some of the later designs except that the grounded metal coverings of the barriers around the disconnecting contacts and some of the busses are omitted.

Each feeder is provided with a permanent oil-immersed metal-clad ground and test switch by which the feeder may be connected to either ground or the test bus. An installation of these switches is shown in Fig. 6. The test bus may be grounded through an oil circuit breaker of proper closing characteristics to ground a feeder successfully even though alive from backfeed. The ground and test switches for the bifurcated feeders also have disconnecting switches built into them so that either branch may be disconnected and grounded or tested while the other is in operation. As these disconnecting switches are not suitable for opening under load, the feeder breaker is always opened and the circuit grounded before a branch of the feeder is disconnected or connected, and the feeder then restored to service.

Control and Relaying

Switching and generator control is effected at unit-type steel control cubicles, one for each generator and one for each associated section of feeder breakers and selector breakers. (See Fig. 7.) This arrangement was an endeavor to reduce the likelihood of operating error by making the control units distinct and has proved to be very satisfactory. It is also believed that a control wiring fire would not spread beyond the one unit. Lead-covered multiconductor control cables are installed in ducts throughout, except as flameproof single-conductor wires are required within control cubicles or switch mechanisms.

Voltage and frequency are hand controlled. A bell alarm and indicating lights immediately call the operator's attention to the automatic tripping of a breaker, and balanced current relays on the 2

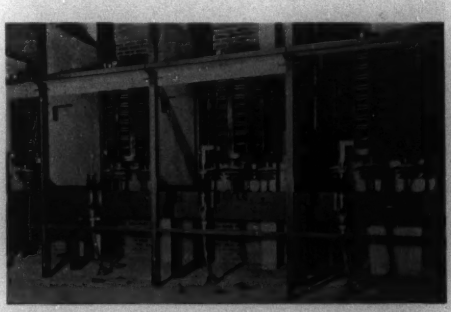

Fig. 5. Feeder reactor installation with aisle barriers removed

Asbestos board barriers are between reactors and completely separate reactors from the aisle. These latter barriers, which have been removed for the photograph, cannot be opened unless the feeder breaker is open and the circuit grounded

branches of the bifurcated feeders indicate on which of the 2 branches the fault occurred.

A schematic diagram of relay protection on a typical section of 27-kv bus is given in Fig. 8. Feeder breakers are protected by induction type

overcurrent relays energized from bushing current transformers in the circuit breakers, and such feeders as are not tied directly to another high voltage grounded circuit are also protected by ground relays. The selector breakers are equipped with induction overcurrent relays having characteristics and settings such that they will back up the feeder breaker and trip if the latter fails to trip a feeder short circuit, but will trip ahead of the feeder breaker in case of feeder reactor failure. Each section of the synchronizing bus is relayed differentially and is backed up by overcurrent protection on the breakers between the synchronizing bus and the generator or so-called *H* bus. The generators and autotransformers are relayed differentially as a unit and in addition, all units except the last 2, which have double winding autotransformer operation, are equipped with current balance relays on the parallel windings.

Operating Experience With the Scheme of Connections

While Hudson Avenue Station was originally designed for feeding substations and without any

Fig. 6. Double ground and test switch installation

Each feeder may be connected to a metal-clad test bus or grounded by a permanent ground and test switch. The switches for the bifurcated feeders also include disconnecting features for each branch of the feeder

major ties to other 60-cycle stations, it has fitted in with the changed methods of distribution in a very satisfactory manner. The direct supply to the low-voltage a-c network has become the major method of distribution, and ties with the Hell Gate station of The United Electric Light and Power Company were a significant item in the selection of the later large-sized units and will become increasingly important as the loads in the territory develop.

The supply to the network has been secured following the same general principles used in feeding the substations; that is, feeders closely adjacent in a network area are connected to separated busses at the generating station, except that 2 feeders supplying a single street and subject to the same exposure by reason of being in a common duct bank may originate from a common bus. The supply to the network has introduced new problems, such as the necessity for closer voltage control and for maintaining minimum phase angles between bus sections. The direct supply to the network through feeders from the generating station without feeder regulators has placed the burden of voltage regulation on the station. This has been met by installing larger and more accurate generator voltmeters and varying the station voltage with load according to a voltage schedule. It has been possible to maintain a better average and a narrower range of delivered voltage than is received from the radial system with individual 4,000-volt feeder regulators.

The low-voltage network forms a low voltage tie between generating station bus sections which limits short circuits on it to such comparatively small magnitudes that they have little or no effect upon generating station operation. It might appear, therefore, that the network would furnish the tie between station units necessary for synchronizing and load transfer purposes and complete isolation between units within the station might be obtained. However, the network has certain characteristics which make load transfer facilities at the generating station even more desirable than when the latter feeds only distribution substations. The impedance between units feeding the network is not uniform, varying from a minimum where 2 or more network units are connected to a customer's bus, to a maximum where units are several blocks apart. As the transformer units are small compared to the feeder capacity, the circulating currents through some units, due to small differences in bus phase angle or voltage, may be out of all proportion to those in the feeders as a whole. As a result, advancing the phase angle of a bus section may load up a few network units, even with all feeders in service, before the total load transfer through the network becomes appreciable. The large number of small transformers closely related to local loads, connected to each feeder, requires that the feeders be out of service frequently for maintenance and construction purposes, with the result that scarcely a day goes by when one or more feeders from a station supplying 75 or 100 are not out of service. As the loadings on a few transformers adjacent to feeder that is out may be the limiting feature in load transfer through the network, the spare capacity installed in transformers and feeders for these so-called contingency conditions rarely can be used for load transfer purposes. It is desirable, therefore, to keep phase-angle differences between busses small, generally within about one degree. The transfer capacity of the synchronizing bus and the ability to connect each feeder group to either of 2 generators have made it possible to adjust the number of operating machines and their loadings for best economy consistent with proper running reserve and still keep the phase differences between busses within 0.5 deg most of the time.

When the connected station capacity is approximately 400,000 kw or more, the synchronizing bus is operated in 2 sections so as to keep possible short-circuit currents within the break ratings. The synchronizing bus is sectionalized in such a way that one or both of the 2 large units are connected to both

Fig. 7. Control room

Segregated steel control panels are installed for each generator and each section of feeders

sections, thus tying them together through the impedance of the double-winding autotransformers.

The double-winding principle and the spreading of the connections of the 2 160,000-kw units through the bus have been very helpful in maintaining proper voltages and phase angles in spite of the relatively large proportion of load carried by these units. Some further improvement might have been made by interchanging the connections of No. 6 unit with the nearest connection of No. 7 unit, thereby making it possible to connect all bus groups directly to one or the other of the 2 largest units (see Fig. 1), but it was believed that the gain would not be sufficient to warrant the added expense and complication. Somewhat closer regulation of voltage and phase angles might be obtained by making the connections to the synchronizing bus through autotransformers, or windings in the generator autotransformers, equipped with load-ratio control. Experience to date indicates that this is not necessary where there is some flexibility in connecting feeders to machines.

Some thought has been given to the possibility of eliminating the synchronizing bus entirely and thereby securing even greater segregation and reduction of short-circuit currents. This could be accomplished by providing adequate transfer facilities so that feeders could be switched among machines to secure the desired loadings on each unit. Such a scheme might involve extensive switching equipment and operations where the station is designed with many small bus sections, with the associated increased costs and hazards, and would lose the advantages of a back-up supply for all feeders in case of loss of a generator. The loss of a heavily loaded generator to which many feeders were connected, and the transfer of load to a lightly loaded generator to which few feeders were connected, might set up serious load and voltage disturbances in the distribution system until feeders could be transferred to the new source in the station.

The synchronizing bus or tie bus also furnishes an excellent point for connection of any large station-to-station ties in that it can deliver power from or receive power into the station with a minimum unbalancing of the loadings or phase angles of individual feeder bus sections. At the Hudson Avenue Station, the frequency changer tie to the 25-cycle system is made on the synchronizing bus, but the various ties to the 60-cycle Hell Gate Station and system of The United Electric Light and Power Company are at present distributed among the various feeder sections. These ties are in a state of transition and at present consist of 2 40,000-kva 27-kv ties with load-ratio control for ordinary load transfer purposes. These are operated to keep the busses of the 2 stations in phase with each other regardless of the load transferred across these ties. In addition, there are 10 27-kv so-called "tapped ties" without load-ratio control between Hudson Avenue and Hell Gate, and 2 27-kv feeders from Hudson Avenue that are tied to 13-kv feeders from Hell Gate by means of autotransformers in substations of the New York and Queens Electric Light and Power Company. These "tapped ties" average about 15,000-kva capacity each and are used to feed network and substation load in Brooklyn and Queens.

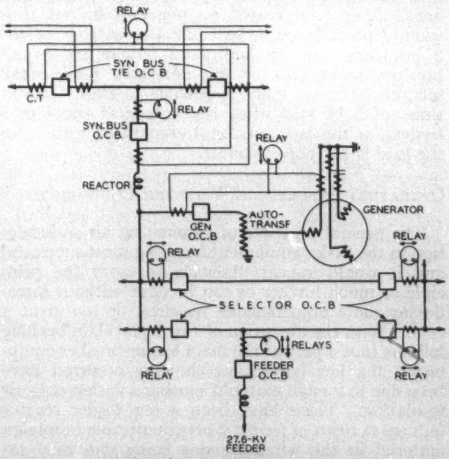

Fig. 8. Schematic diagram of relay protection on a typical section of 27-kv bus

In general, back-up protection has been provided, so that if one breaker or relay fails, the next in series will trip

They are not used normally for load transfer purposes because they feed into networks also supplied by radial feeders from the generating stations, and forcing load from one station toward the other would produce bad load distribution between transformers

fed from the "tapped ties" and those from closely associated radial feeders.

There are 12 27-kv 15,000-kva feeders which energize 13-kv feeders in lower Manhattan through autotransformers. These feeders supply substation and network load which also is fed by cables from the Hell Gate station. Here again there is no attempt to shift the load from one station to the other through the network because of the bad loading conditions that would result. However, the "tapped ties" through Queens and the "secondary intermesh" in lower Manhattan, as the installations are called, furnish added synchronizing power and stability between the stations and could be used for power transfer purposes during an emergency. These advantages were secured at little cost under present load conditions, but as the loads increase, and additional power transfer is needed or becomes economical under normal conditions, there will undoubtedly be some changes from the present connections.

The small bus sections have worked out splendidly. Such bus faults as have occurred have been cleared quickly and affected but a few feeders and have not affected any customer beyond the momentary dip during the failure. The single breaker per feeder and the 4 feeder breakers per 2 selectors have met all requirements. It has been possible to do practically all feeder breaker maintenance when the feeder was necessarily out for some other purpose. This is a little more difficult to accomplish when there are 2 feeders bifurcated on one switch, but it is usually possible to so schedule the outages of the 2 branches that an additional outage for circuit breaker maintenance is not necessary. The small sections of busses make it possible to clean them at times of light load when the outage of the 4 or 8 feeders, as the case may be, to separated sections of the load is not objectionable.

Operating Experience With the Equipment

The general principle of eliminating air as insulation in the 27-kv equipment has been most successful and it would appear desirable to carry the principle as much further as can be done without introducing more objectionable features, or too great a cost. With the exception of 1 or 2 porcelain bushing failures (not a part of the main bus or breaker equipment) the few failures which have occurred have been due to foreign material causing a flashover in air insulation. These have been a few feeder reactor failures at times of feeder short circuits due to foreign material in the windings, one being due to a rat finding a small opening and trying to climb a reactor insulator. In none of these cases was there any spread of the trouble. A serious reactor failure took place in the early days before the barrier installation was completed when one of the large reactors in a generator connection to the synchronizing bus was flashed over, probably due to being touched with a wooden scale, and badly burned. This spread to one adjacent feeder reactor and blistered and scorched some of the bus insulation and breaker disconnecting contact barriers but caused no other damage.

The most serious failure took place recently when apparently an over ambitious workman got some foreign material through the opening in the disconnecting contact barrier while a generator circuit breaker was down for maintenance. The flashover of the live bus insulator set fire to the protecting barrier and bus insulation and to an oil filter press standing below, and most serious of all, resulted in the only electrical operating fatality of the station. Enough soot from the burning insulation and oil deposited on other insulators, even through the small openings where the breaker bushings project into the barriers, so that one feeder breaker's stationary bushing arced over about 15 min later, but did not result in any fire. The readiness with which the insulation material burned and the fact that so much soot found its way into the breaker disconnecting contact bushings within the room, was somewhat disappointing.

The results of the failures as contrasted with failures involving live parts in older cell-type breaker and bus construction, even at 6,600 volts, has demonstrated the superiority of the later construction. Metal-clad switch gear which was not available when the station was built goes a step further, but also has its own disadvantages. It is doubtful whether metal-clad switch gear would have prevented this failure, and it is quite possible that the failure of the stationary disconnecting bushing would have released and ignited oil resulting in a more serious fire. The closer fit around the disconnecting bushings might have prevented the dangerous deposit of soot on the bushings of the other breakers. On the other hand it would be more difficult to cut clear damaged equipment to restore service and the larger amounts of inflammable oil or compound which might be released by a failure would introduce some additional fire hazard. However, it is believed that the complete surrounding of high voltage parts by grounded metal is a step in the right direction in reducing risks of failures and preventing the spread, should a failure occur. It is to be hoped that advances in designs and materials will bring equipment that can be cut clear more readily if trouble occurs in any part and will reduce the fire hazard of inflammable materials. Metal-clad reactors were studied for the latter part of the station, but cost, losses, space, and oil fire hazard brought the decision to continue the station with the open concrete core reactors having turn insulation instead of the earlier bare conductor type.

The breakers themselves were put into operation and have been maintained with comparatively little difficulty. The screw elevating and disconnecting features, such as have now become common on some metal-clad designs, have been highly satisfactory. The clamping and interlocking can undoubtedly be simplified and cheapened in cost, but the operation has been entirely satisfactory. As compared with a group of 7 33-kv metal-clad switch gear units in a substation of the company, for which there is one movable elevating platform, the built-in elevating features of the Hudson Avenue breakers is much safer and the speed with which a breaker may be lowered for disconnecting purposes, or raised and

restored to service, is particularly valuable where feeders must be disconnected fairly frequently. There have been a few cases of internal flashover of breakers in substations having the same design as the feeder breakers except for truck mounting. Tests indicate that this possibility can be removed by slightly internal barrier changes and additions. This will probably be undertaken although there have been no generating station breaker troubles. Some studies have been made looking toward the increase in interrupting rating of the bus breakers by installing oil blast features in place of the explosion chambers. This is not necessary now but may be undertaken later to increase the margin between breaker rating and possible short circuits when load conditions require more machine capacity on the bus and greater interstation tie capacity. (See Table I.)

The ground and test facilities have been decidedly valuable in making it possible to ground or test a feeder promptly and safely. The separate grounding breaker, designed to be able to close onto a short circuit, has been used to ground a feeder and force out a network switch which failed to trip on cable charging current, or transformer exciting current. Somewhat faster and more satisfactory operation would be secured if the double ground and test switches used on the bifurcated feeders, were capable of opening or closing load current at full voltage so that it would not be necessary to deënergize and ground both branches before one branch can be connected or disconnected. However, the need for placing the double ground and test switch in the space provided for a single switch made it impossible to provide such a design. It is not believed that the ability to clear or restore one branch of a bifurcated feeder without the necessity of killing and grounding the whole circuit would justify any very expensive refinements.

The precautions taken in the building construction to prevent a failure spreading from one phase to another, or from one section to another, have been entirely successful at least as far as any failures to date are concerned. They have, however, made adequate ventilation more difficult. There is some condensation under certain atmospheric conditions, and in a new station it would be desirable to provide facilities for more rapidly clearing out smoke should a fire occur. Perhaps by the time the next station is built satisfactory breakers without inflammable fluids will be generally available.

Control and Relay Operation

The general control system has been as satisfactory as anticipated. The principle of keeping the number of instruments, control devices, etc., to the minimum really necessary for operation, and have those stand out clearly as well as have each panel distinct, has aided operation. As an aid to general system load dispatching, remote load indicating and totalizing equipment is now being installed to give the load of the principal stations of the Consolidated Gas system in the central system operators' room.

Some study has been given to the advisability of adding automatic voltage control, or at least an automatic means of rapidly increasing excitation in emergency, but these studies and experience indicate that the load and generator characteristics are stable at present. The most trying of these experiences have been the loss of field on the most stable unit in operation at the time, the pulling out of step of the least stable unit, and the sudden tripping out of a 110,000-kw unit due to flashover of its terminals when a cooling radiator sprang a leak. In all cases the remaining units stayed in step and while the voltage dropped momentarily, approximately 60 per cent in the worst case, it was immediately restored.

Some improvements in feeder relaying might be secured by installing the current transformers beyond the reactors rather than in the breaker bushings. This would permit faster feeder relay settings by avoiding the necessity of a time differential between the feeder and selector breakers in case of reactor failure, and would have avoided the possibility of a feeder breaker attempting to open a reactor failure in case of improper timing of relays or breaker tripping. The faster feeder breaker operation was not an advantage when the system was designed due to the necessity of selecting with substation breakers and at present would be advantageous only on purely network feeders. The installation of bushing current transformers in the breakers of the single branch feeders probably made a safer and certainly a much cheaper installation than would have been secured by cutting into the lead-covered feeder cables and installing separate current transformers. A change might have been made when the double ground and test switches were installed by using bushing current transformers in them, but it was believed that the cost of making the changes could not be justified by the improved operation.

Relaying has functioned well. Such failures as have occurred have been cleared with a minimum disturbance to the system. The results are a vast improvement over our old stations operated in 1 or 2 solid busses.

Conclusion

The station was designed as part of a definite distribution system, adapted to equipment and devices available at the time. There were compromises between cost and a closer approach to technical perfection, and choice often had to be made between the advantages and limitations of one design and somewhat different advantages and limitations of another method. But such is always an engineer's job. The station has operated with a high degree of continuity of service and safety to personnel. A review of the experience with this station leads its designers to look with favor toward even greater simplicity and approach toward the unit principle. It is hoped that its design was a small step forward, and that the results of its design and operation may prove helpful in the planning of later station control schemes and equipment that have and will come after it.

Attenuation and Distortion of Waves

The conventional theory explaining the attenuation and distortion of traveling waves is not adequate to explain many peculiarities found to exist in such waves. In this paper there is developed a multi-conductor multi-velocity theory of traveling waves which more completely explains wave behavior. The conventional traveling wave theory is shown to be a special case of this more general theory.

By
L. V. BEWLEY
ASSOCIATE A.I.E.E.

General Elec. Co., Pittsfield, Mass.

CATHODE ray oscillograms of artificial lightning surges on transmission lines show many peculiarities which cannot be explained by conventional traveling wave theory. Some of these are: (1) The attenuation is much greater than can be accounted for by the losses, and is less for a surge on all the conductors of the system than for an equal surge on only one of the conductors, (2) as a surge travels along a line a pronounced step may develop in the wave front while (3) a loop of reversed polarity appears at the front of waves induced on adjacent conductors, (4) the attenuation is much greater for the inducing wave than for the induced wave, so that eventually both waves become substantially equal, (5) flat spaces develop on the tail of the surge, (6) the aggregate velocity of waves may be much less than that of light, (7) the coupling varies greatly with distance traveled, (8) voltage and current surges become dissimilar in shape, and (9) the steepness of the wave front may apparently first decrease and then increase.

These and many other facts follow as a natural consequence of the multi-conductor multi-velocity theory of traveling waves developed in this paper. It is shown that attenuation and distortion are largely due to these multi-velocities rather than entirely to losses as generally supposed. These multi-velocities are called into existence by either or both of 2 effects: (1) Zero potential planes for the electrostatic and electromagnetic fields are at quite different depths below the ground surface, and (2) effective conductor radii are different for the 2 fields on account of the corona envelope. In the light of this theory distortion becomes a comparatively simple concept, and such things as the reason why chopped waves attenuate much more rapidly than long waves becomes obvious. Open end adjacent conductors no longer merely "float" in the field of inducing waves, but give rise to powerful and unexpected reactions. The conventional traveling wave theory is a special case of this more general theory and may be delimited by it. In most practical applications the old theory suffices.

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Conventional Theories Require Modification

It is ordinarily supposed that the attenuation and distortion of traveling waves are the direct result of energy losses. Conventional transmission line theory based on a single conductor and fixed constants R, L, C, and G will yield no clue to the mechanism of attenuation and distortion, except for the effect of the losses as represented by the series resistance R and shunt conductance G. Attempts have been made to include skin effect in the calculations, and to approximate the discontinuous action

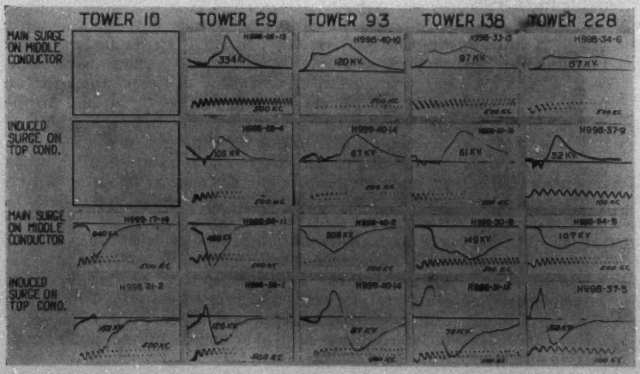

Fig. 1. Impulse tests on transmission lines to study coupling and attenuation

Voltage induced on a parallel conductor free from electrical connection

of corona, but these efforts have led to great mathematical complication, and they have failed to account for the peculiar distortions observed with impulse traveling waves on transmission systems. Moreover, the attenuation chargeable to such energy loss is far too small. When the single conductor theory is abandoned for the more complex multi-conductor theory based on all waves having the velocity of light[1,4,5,6] the results continue to be disappointing; for the linear nature of the equations compels all waves induced on adjacent conductors to be exact replicas of the parent wave, which is quite contrary to the observed facts. Apparently then, the conventional theories require some radical modification to agree with the facts. It is the object of this paper to present such a modification, and to show that on a multi-conductor system the waves move at different velocities, and a large part of attenuation and distortion is due simply to these differences in velocity. Furthermore, these differences in velocity have nothing to do with energy losses. Bekku and Satoh have shown the presence of algebraically different velocities on the completely transposed single and double-circuit 3-phase lines.[2,3] However, they calculated these algebraically different velocities all to be equal numerically to the velocity of light. It has further been shown that, in general, there can exist simultaneously on an n-conductor system waves with n different velocities of propagation.[4,5,6] But in the case of overhead conductors these different velocities all become equal to the velocity of light, provided that the radii of the conductors and the zero potential plane are the same for both the electrostatic and electromagnetic fields. This paper shows that this proviso is untenable in many cases; particularly with respect to attenuation, distortion, and coupling.

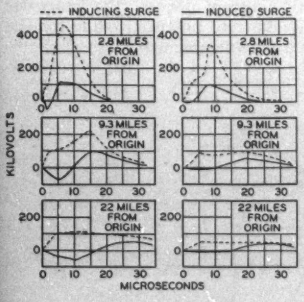

Fig. 2. Curves plotted from oscillograms taken on a transmission line with artificial lightning surges (from Brune and Eaton)

Typical Impulse Tests on Transmission Lines

During the summers of 1930 and 1931 an interesting series of experiments was conducted on the *S* 19 line of the Consumers Power Company and reported in several A.I.E.E. papers.[7,8] In Figs. 1, 2, and 3 are shown the attenuation and distortion experienced by the main, or parent surge impressed on one conductor, as well as that experienced by the accompanying surge induced on an adjacent conductor.[8] There are 6 points of particular interest disclosed by these oscillograms:

1. As the main surge moves along the line it acquires a pronounced step in its front. That this cannot be due to corona is evidenced by the fact that it is present even when the wave is definitely below the corona level.

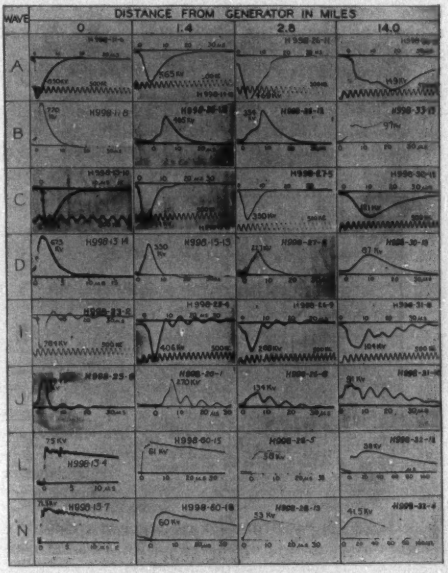

Fig. 3. Attenuation of traveling waves

Waves A, B, I, J, and L applied to one conductor only; waves C, D, and N applied to 3 conductors

2. As the induced surge moves along the line it acquires a pronounced loop of reverse polarity at its front. This loop cannot be due to corona, for it develops even when the main wave is far below the corona level, and for a positive wave—which causes a greater amount of corona—the loop is smaller, or may actually disappear.

3. Both the main and the induced surge become elongated with travel, but the main surge is attenuated much more than the induced surge; so that eventually they are of practically the same size.

4. Short surges, such as those chopped by an insulator flashover, attenuate much more rapidly than long surges. Positive surges suffer a greater attenuation than negative surges.

5. The induced wave is initially greater for a positive than for a negative wave.

6. Equal surges on all 3 conductors attenuate less than an equal surge impressed on only one conductor, but the wave front is flattened much more.

The theory which is developed in this paper explains all of these facts and shows conclusively that they are a natural consequence of different radii of conductors and different zero potential planes for the electrostatic and electromagnetic fields.

In 1930 Foust and Menger[9] developed an empirical formula for attenuation which has proved valuable

1. For all numbered references see list at end of paper.

in certain engineering calculations, but which gives no insight into the mechanism of attenuation.

E. W. Boehne[10] has offered an explanation of the effect of corona on the attenuation and distortion of traveling waves. His theory explains the reduced velocity of the surge and the increased surge impedance, and attempts also to present a plausible reason for the step which develops in the front of the main surge. It does not, however, tell why this same step develops without corona, nor does it explain the peculiarities which appear in the induced surge. Apparently other influences are present.

Brune and Eaton[8] have supplied a somewhat different explanation of the effect of corona. Their theory leads to an attenuation which is roughly linear. They do not attempt to find the reason for the distortion associated with the induced surge,

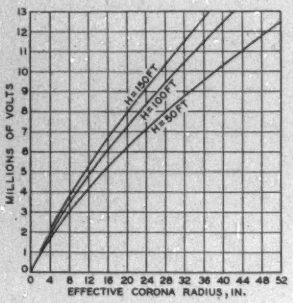

Fig. 4. Effective radius of corona on line conductors

beyond pointing out that the mechanism apparently involves a separation of charge on the isolated conductor.

Effective Radius of Corona Envelope and Equivalent Ground Planes

The effective radius R of the corona envelope surrounding a conductor carrying a high voltage surge was first determined by E. M. Hunter.[11] His method, since used by Fortescue,[12] and by Torok and Ellis,[13] is briefly as follows. The capacitance to ground of a cylindrical conductor of radius R and height H above ground is

$$C = \frac{1}{2 \log (2H/R)}$$

The radius R of the corona envelope is assumed to be that radius at which the gradient is just equal to the critical corona gradient of 76 kv/in. The gradient is

$$g = \frac{2Q}{R} = \frac{2\,CE}{R} = \frac{E}{R \log (2H/R)} = 76 \text{ kv/in.}$$

or

$$E = 76\,R \log (2H/R)$$

This equation is plotted in Fig. 4 for representative values of E and H. Now the electrostatic field corresponds to this effective radius of conductor, but not so the magnetic field. The current wave is still restricted to the metallic conductor, although probably concentrated at its periphery due to transient skin effect. Therefore, in calculating the electrostatic coefficients a larger radius must be used than in calculating the inductance coefficients. Furthermore, if the different conductors of a multi-conductor system are carrying surges of different potentials, then the effective corona radius will be different for each conductor. If the voltages are below the corona voltage, then the electrostatic coefficients must be figured on the basis of the metallic conductor.

It is well known that the equivalent zero potential plane with respect to zero sequence and third harmonic currents on power systems is at a considerable depth below the ground plane. This is also true for the comparatively high frequency currents used in telephone practice. The depth of the equivalent image depends upon the resistivity and stratification of the soil, and on the frequency. On the other hand, the zero potential plane with respect to the electrostatic field appears to lie very near or at the ground surface. In conventional traveling wave calculations it has always been assumed that the zero potential plane was the same for both the voltage and current waves, and this plane has habitually been taken as the ground surface. Torok and Ellis[13] have recently published data indicating a relationship between the depth of the equivalent ground plane and the tower footing resistance. But it appears to the author that there is not 1 but 2 zero potential planes, Fig. 5, one of which is associated with the voltage waves (the electrostatic field) and the other with the current waves (the magnetic field). Apparently the zero potential plane for the current wave is at a considerable depth.

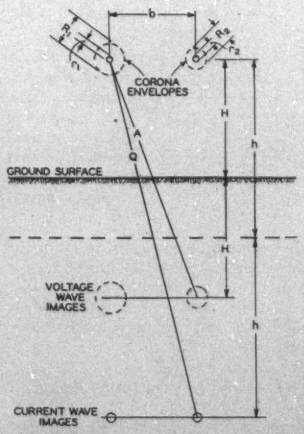

Fig. 5. Corona radii and position of images

The general situation for a 2-conductor system is shown in Fig. 5. The corona radii are shown different for the 2 conductors, since they may be carrying different voltage waves. The electrostatic and electromagnetic coefficients are given in Appendix I.

General Theory

The analysis rests, unfortunately, on the complicated multi-conductor multi-velocity theory of traveling waves.[4,5,6] In Appendix I this has been carried out in detail for the 2-conductor system of Fig. 5, and in Appendix II it has been generalized to apply to any number of conductors.

On the 2-conductor system it is found that there are on each conductor 2 waves with different velocities:

$$e_1 = f_1(x - v_1 t) + f_2(x - v_2 t)$$

$$e_2 = a_1 f_1(x - v_1 t) + a_2 f_2(x - v_2 t)$$

where the velocities v_1 and v_2, and likewise the fixed proportionality factors a_1 and a_2, depend only on the capacitance and inductance coefficients. There are corresponding current equations. The relative magnitudes, shapes, and polarities of the 2 waves $f_1(x - v_1 t)$ and $f_2(x - v_2 t)$ are determined solely from the terminal and initial conditions. For example, suppose a surge $E(t)$ is impressed on conductor No. 1 by

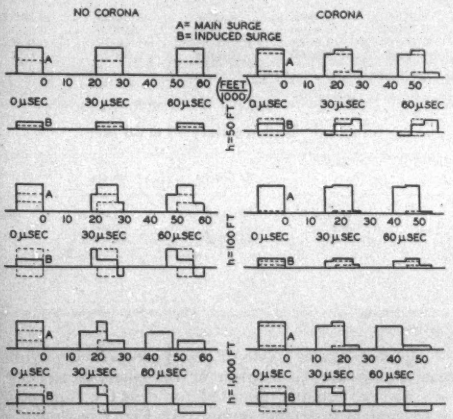

Fig. 6. Effect of corona and depth of current images

an impulse generator, while conductor No. 2 is open-ended. Then since the current must be zero at the open end, $x = 0$, while the 2 waves on conductor No. 1 must add up to $E(t)$ at $x = 0$, there are sufficient data to determine $f_1(x - v_1 t)$. This has been done in Appendix I and it is found that the 2 surges are

$$e_1 = \frac{1}{1-w} E\left(t - \frac{x}{v_1}\right) - wE\left(t - \frac{x}{v_2}\right) = e_1' + e_1''$$

$$e_2 = \frac{1}{1-w} a_1 E\left(t - \frac{x}{v_1}\right) - a_2 wE\left(t - \frac{x}{v_2}\right) = a_1 e_1' + a_2 e_1''$$

where w is a factor involving the circuit constants. Thus at $x = 0$

$$e_1 = E(t)$$

$$e_2 = \left(\frac{a_1 - a_2 w}{1-w}\right) E(t)$$

Now the 2 component waves are moving at different velocities, so that eventually they part company, and so the ratio

$$\frac{e_2}{e_1} = \text{(coupling factor)}$$

is a variable quantity depending upon how far the waves have traveled and the relative magnitudes and polarities of the component waves. Thus initially

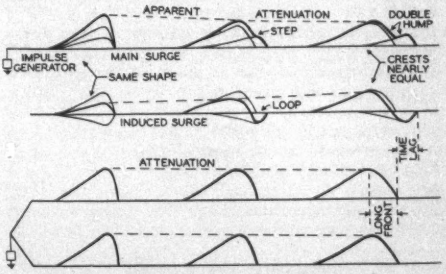

Fig. 7. Typical attenuation and distortion effect

the coupling factor may be 35 per cent while later on it becomes 100 per cent. It is also evident that if e_1' and e_1'' are the same polarity while a_1 and a_2 are of opposite sign, then as the 2 component waves disengage e_1 experiences greater attenuation, while e_2 may actually increase in magnitude! It is also seen that a step will develop in e_1 on account of the faster wave running ahead, while the whole surge becomes elongated, and a negative loop will appear in front of the induced wave on conductor No. 2. It remains to prove by numerical examples that the calculated polarities, velocities, and magnitudes are compatible with the oscillographic records and to show that the effect of corona may be predicted accurately from this theory.

Numerical Examples

The effect of varying the position of the magnetic zero potential plane and the corona envelopes of Fig. 5 is given in Table I, calculated according to Appendix I. The distance between conductors is kept constant at $b = 15$ ft, and likewise the electrostatic zero plane is assumed to remain constant at the ground surface, $H = 50$ ft. The magnetic zero plane is taken at $h = 50$, 100, and 1,000 ft, respectively. When there is no corona the metallic conductor radius is used to calculate both the coefficients. When corona is present the envelope for the main surge is taken as 3 in., which corresponds to 1,370 kv, while that of the induced surge is taken as one inch corresponding to 540 kv. Table I gives complete data on the magnitudes, velocities, and polarities of the 2 wave components on both conductors. These results have been plotted in Fig. 6 for rectangular waves and in Fig. 7 for typical lightning surges.

Table I—Numerical Examples; Effect of Varying h and R of Fig. 5

b = 15 ft	No Corona			Corona		
$h_1 = h_2 = h$ (ft)	50	100	1000	50	100	1000
$r_1 = r_2 = r$ (in.)	0.5	0.5	0.5	0.5	0.5	0.5
$(L_{11} = L_{22}) \times 0.5 \times 10^9$	7.775	8.47	10.77	7.78	8.47	10.77
$L_{12} \times 0.5 \times 10^9$	1.89	2.585	4.88	1.89	2.585	4.88
$H_1 = H_2 = H$ (ft)	50	50	50	50	50	50
R_1 (in.)	0.5	0.5	0.5	3	3	3
R_2 (in.)	0.5	0.5	0.5	1	1	1
$K_{11} \times 18 \times 10^{11}$	0.1366	0.1366	0.1366	0.1825	0.1825	0.1825
$K_{22} \times 18 \times 10^{11}$	0.1366	0.1366	0.1366	0.1545	0.1545	0.1545
$K_{12} \times 18 \times 10^{11}$	−0.0333	−0.0333	−0.0333	−0.0492	−0.0492	−0.0492
$I_{11} = (L_{11}K_{11} + L_{12}K_{12}) \times 9 \times 10^{20}$	1.00	1.070	1.307	1.327	1.419	1.729
$I_{12} = (L_{11}K_{12} + L_{12}K_{22}) \times 9 \times 10^{20}$	0.00	0.068	0.306	−0.091	−0.017	0.225
$I_{22} = (L_{22}K_{22} + L_{12}K_{12}) \times 9 \times 10^{20}$	1.00	1.070	1.307	1.110	1.183	1.425
$I_{21} = (L_{22}K_{12} + L_{12}K_{11}) \times 9 \times 10^{20}$	0.00	0.068	0.306	−0.038	0.055	0.361
v_1/(vel. of light)	1.00	0.937	0.787	0.863	0.840	0.726
v_2/(vel. of light)	1.00	0.999	0.999	0.955	0.918	0.892
$a_1 = (1 - v_1^2 I_{11})/v_1^2 I_{12}$	0.244	1.000	1.000	−0.203	0.23	0.762
$a_2 = (1 - v_2^2 I_{11})/v_2^2 I_{12}$	0.244	−1.000	−1.000	2.55	13.65	−2.11
w	−1.000	−0.568	−0.477	−0.211	−0.006	−0.149
$e_1(v_1)$	0.500	0.638	0.677	0.826	0.994	0.871
$e_1(v_2)$	0.500	0.362	0.323	0.174	0.006	0.129
$e_2(v_1)$	0.122	0.638	0.677	−0.168	0.228	0.664
$e_2(v_2)$	0.122	−0.362	−0.323	0.444	0.080	−0.272
e_1 (initially)	1.000	1.000	1.000	1.000	1.000	1.000
e_2 (initially)	0.244	0.276	0.354	0.276	0.308	0.392
$i_1(v_1)$	0.00107	0.00103	0.00092	0.00229	0.00238	0.00153
$i_1(v_2)$	0.00107	0.00103	0.00092	0.00016	−0.00005	0.00055
$i_2(v_1)$	0.00000	0.00103	0.00092	−0.00096	−0.00019	0.00073
$i_2(v_2)$	0.00000	−0.00103	−0.00092	0.00096	0.00019	−0.00073

A survey of Fig. 6 brings out several important facts:

1. When the current and voltage images coincide and the conductor radii are the same for both the voltage and the current waves, then there is but a single wave moving at the velocity of light. Neglecting losses, neither the main wave nor the induced wave suffer attenuation or distortion.

2. Increasing the depth at which the current images are located, brings into existence waves with 2 different velocities on each conductor. Since these waves travel at different velocities they separate with distance traveled. A step develops at the front of the main surge, while a loop of reversed polarity appears leading the induced surge. As the waves disengage, the amplitude of the main surge decreases, but, neglecting losses, the amplitude of the induced surge may actually increase, so that eventually both surges become practically equal. The separation of the component waves creates the impression of a simple elongation such as is associated with series resistance losses. So far as the author knows, a complete separation of the component waves has not yet been observed in experimental lightning studies, although there are several cathode ray oscillograms of both natural and artificial lightning surges which show the double humps characteristic of this separation. Of course, the elongating effect of series resistance losses will tend to keep the component waves joined.

3. Corona increases the size of the conductors with respect to the electrostatic field. In the calculation of Table I and Fig. 6 it was assumed that the voltage of the main surge was about 1,350 kv and that of the induced surge about 500 kv. By Fig. 4 these potentials correspond to radii of 3 in. and 1 in., respectively. In Fig. 6 it is shown that corona alone causes a step in the front of the main surge and a hump at the front of the induced surge. Thus the effect of corona and of depressed current images are similar on the main surge characteristic, but opposite on the induced surge characteristic. It might therefore be suspected that there are critical corona radii and depths of current images at which the 2 effects will nullify each other. In the case of h = 100 and corona on the conductors, this idea is supported by Fig. 6. It is seen that the main surge is practically a single wave, and the relative importance of the faster wave in the induced surge also has been considerably reduced. The principal part of the surge, represented by the slower wave, suffers a considerable reduction in velocity. Thus at 60μ sec the distances traveled are as in Table II.

Table II—Distance Traveled at 60 μsec

h	No Corona	Corona
50 ft	60,000 ft	52,000 ft
100 ft	56,000 ft	50,000 ft
1,000 ft	48,000 ft	43,500 ft

The rectangular waves of Fig. 6 give a clear picture concerning the mechanism of the phenomena, but are not particularly adapted for direct comparison with typical lightning surges. In Fig. 7 is shown a plot using typical lightning surges. Its counterparts among the oscillograms of Figs. 1, 2, and 3 are easily identified. The great variety of surge shapes which appear on transmission lines are not surprising when it is appreciated that the magnitudes, velocities, and polarities of the component waves all affect the resulting shape; nor from this point of view is there any mystery concerning the radical change in shape experienced by a surge as it travels along the line. Another point of some interest which has occasioned comment in the past is the dissimilarity in shape between the voltage and current impulses. This has been explained as due to a "variable surge impedance." In the light of the multi-velocity theory of traveling waves this dissimilarity is to be expected; for the surge impedances of waves with different velocities are different, and consequently the distortion in the current surge will be different than that in the voltage surge.

Physical Concept

This paper would not be complete without a brief physical explanation for the phenomenon of multi-velocity waves. Consider first Fig. 8, which shows a rectangular wave moving along a transmission line over ground having finite resistivity. The ground resistance is represented by a simple network having vertical and horizontal elements. Now at the instant when the advancing wave front reaches a capacitance element all the voltage is consumed by the ground resistance network, the current following paths somewhat as shown in the sketch. There then ensues a transient redistribution of current, at the termination of which the current paths are all horizontal, there are no vertical components of voltage drop, and consequently the surface of the earth is at zero potential, all the voltage being consumed by the capacitance elements of the line. The depth of penetration of the current depends, obviously, upon the resistivity of the soil, and will be deeper the greater that resistivity. Therefore 2 important conclusions are arrived at: (1) the ground surface quickly becomes a zero equipotential surface with respect to voltage images, and (2) the current images are located at greater depths, depending upon the earth resistivity. In general, then, the voltage and current images are not at the same levels, and in consequence of this difference the velocity of propagation $v = 1/\sqrt{LC}$ is slower than normal, because the inductance is greater than it would be if the current image were at the same level as the voltage image. Another effect of the earth resistance is to flatten the wave front; for on account

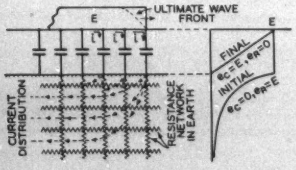

Fig. 8. Current distribution transient

of the redistribution transient, currents continue to flow in the line capacitance elements for some time after the passage of the wave front.

Consider now the effect of introducing a parallel isolated conductor. If the voltage and current images are coincident it merely happens that the voltage induced in the isolated conductor by the currents is exactly equal to that corresponding to its position in the electrostatic field due to the voltages. Under these conditions there is no necessity for a reaction. But if the current and voltage images are not coincident, then the currents tend to induce a different voltage in the isolated conductor than corresponds to its position in the electrostatic field. There can be no resultant current in the isolated conductor (since it is connected to no source) and therefore the only way it can react against these conflicting influences is by a separation of charge. This separation requires time. The mechanism by which it is accomplished is by means of current waves of equal magnitude but opposite polarity traveling at different velocities. Associated with these current waves are corresponding voltage waves, but the surge impedances for the 2 pairs are different.

A trapezoidal surge impressed on one conductor in the presence of another isolated conductor is shown in Fig. 9. The current paths are indicated by arrows. Initially there is no current in the induced surge. After the surge has resolved into its 2 components it is seen that each one of the smaller pair is equal and of opposite polarity, but they involve no net ground current. Consequently they travel at the velocity of light, and do not experience flattening of the front on account of ground resistivity. But those of the larger pair involve heavy ground currents, therefore, travel at a slower speed, and suffer considerable flattening of the wave front. It is obvious that if equal surges were applied to both conductors there would be no further resolution and the surges would propagate as simple, slow velocity waves, but would experience the flattening of the front characteristic of surges carrying ground currents.

The above ideas are illustrated in Fig. 7 for surges of typical shapes when waves are applied to one or both conductors. Notice, in the case of an isolated conductor, how first a step and then a camel's hump develops in the main surge, while a loop appears in the induced surge; the "apparent" attenuation is less for the induced than for the main surge, so that they approach equality; the front of the higher velocity wave is preserved while that of the lower velocity wave is flattened; and the surge is elongated. On the other hand, when equal surges are applied to both conductors only the slow velocity wave exists, but it suffers flattening of the front. However, its attenuation is less, because it

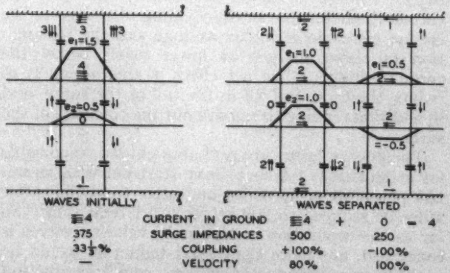

Fig. 9. Resolution of a surge into multi-velocity waves

contains no fast wave component that disengages. Comparing this picture with the oscillograms of Figs. 1, 2, and 3 the agreement is seen to be detailed and exact. In fact, there is hardly any need to remark that C, D, and N of Fig. 3 were for equal waves applied to all the line conductors.

The development of multi-velocity waves on a multi-conductor system is closely analogous to the

development of multi-frequencies in a simple oscillatory circuit when mutually coupled with a number of other such circuits having different independent natural frequencies of oscillation.

Conclusions

The attenuation and distortion of traveling waves are due to 3 principal causes:

1. Multi-velocity waves called into existence by dissymmetry in effective conductor radii and location of the equivalent images for the voltage and current waves, respectively.

2. A slippage effect at higher voltage levels caused by the reduction in velocity of propagation corresponding to the larger diameters of the corona envelopes.

3. Energy losses due to series resistance, skin effect, leakage conductance, and corona.

Of these, the first depends upon the resistivity of the earth and the polarity of the surge. The higher the resistivity the greater the depth to which the equivalent current images are forced, and the more pronounced are both the step which develops in the front of the main surge and the reversed polarity loop leading in the induced surge. On the other hand, the higher the voltage, especially if of positive polarity, the greater the corona envelope diameter and the more the tendency to develop a hump at the front of the induced surge.

But this first factor alone fails in several respects to account for all the observed phenomena. The attenuation is much greater than due to it alone, and the abrupt changes in wave shape called for by it do not always materialize. Rather are the changes in shape gradual. This smoothing process is probably due principally to the variable diameter of the corona envelope, causing the slippage mentioned as the second cause. This may be looked upon in 2 different ways: either as a slowing down of the higher voltage levels on account of the increased corona diameter; or as the yielding of charge to the corona envelope at higher voltage and the reclamation of these charges at lower levels below the corona voltage. The net effect of this action is to reduce the crest and fill in the tail of the surge, and in addition tending to smooth out the contours of the surge.

The energy losses are probably chiefly responsible for attenuation. A surge may start out with an initial potential of 1,000 kv and after traveling a few miles be reduced to 200 kv, or a 5:1 reduction. So far as the separation of the multi-velocity waves is concerned, not more than a 2:1 reduction would be possible on a 2-conductor system; or a 3:1 reduction on a 3-conductor system (assuming all component waves of the same size and polarity); while the reduction in voltage on account of the temporary storage of energy in the space charge is a matter of perhaps 25 per cent. This leaves the greater burden of attenuation on the energy losses. Series resistance tends to elongate a wave, while shunt conductance and corona energy loss tend to contract it. All losses tend to smooth out the irregularities in the surge. Ground resistance flattens the front.

If equal surges are applied to all the conductors of a multi-conductor system, then the resulting surges travel at a single velocity, and consequently the characteristic distortion associated with multi-velocity waves does not materialize. On this account the apparent attenuation is less than when the same surge is applied to only one conductor of the system, but the flattening of the wave front is greater.

Appendix I—2-Conductor System

The differential equations for the 2 conductors shown in Fig. 5 are

$$\left.\begin{aligned} -\frac{\partial e_1}{\partial x} &= L_{11}\frac{\partial i_1}{\partial t} + L_{12}\frac{\partial i_2}{\partial t} \\ -\frac{\partial e_2}{\partial x} &= L_{12}\frac{\partial i_1}{\partial t} + L_{22}\frac{\partial i_2}{\partial t} \\ -\frac{\partial i_1}{\partial x} &= K_{11}\frac{\partial e_1}{\partial t} + K_{12}\frac{\partial e_2}{\partial t} \\ -\frac{\partial i_2}{\partial x} &= K_{12}\frac{\partial e_1}{\partial t} + K_{22}\frac{\partial e_2}{\partial t} \end{aligned}\right\} \quad (1)$$

in which

$L_{11} = \frac{2}{10^9}\log\left(\frac{2h_1}{r_1}\right)$ = self inductance of No. 1

$L_{22} = \frac{2}{10^9}\log\left(\frac{2h_2}{r_2}\right)$ = self inductance of No. 2

$L_{12} = \frac{2}{10^9}\log\left(\frac{a}{b}\right)$ = mutual inductance between No. 1 and No. 2

$K_{11} = \frac{1}{D}\log\left(\frac{2H_2}{R_2}\right)$ = capacitance coefficient of No. 1

$K_{22} = \frac{1}{D}\log\left(\frac{2H_1}{R_1}\right)$ = capacitance coefficient of No. 2

$K_{12} = \frac{-1}{D}\log\left(\frac{A}{b}\right)$ = capacitance coefficient between No. 1 and No. 2

$$D = \left[\log\left(\frac{2H_1}{R_1}\right)\log\left(\frac{2H_2}{R_2}\right) - \left(\log\frac{A}{b}\right)^2\right]18 \times 10^{11}.$$

Notice that the effective radii and distances to the zero potential planes for the capacitance coefficients have been taken differently than for the inductance coefficients. Eliminating the currents in eq 1 there results

$$\left.\begin{aligned} \frac{\partial^2 e_1}{\partial x^2} &= (L_{11}K_{11} + L_{12}K_{12})\frac{\partial^2 e_1}{\partial t^2} + (L_{11}K_{12} + L_{12}K_{22})\frac{\partial^2 e_2}{\partial t^2} \\ \frac{\partial^2 e_2}{\partial x^2} &= (L_{12}K_{11} + L_{22}K_{12})\frac{\partial^2 e_1}{\partial t^2} + (L_{12}K_{12} + L_{22}K_{22})\frac{\partial^2 e_2}{\partial t^2} \end{aligned}\right\} \quad (2)$$

Let

$$\left.\begin{aligned} I_{11} &= L_{11}K_{11} + L_{12}K_{12} \\ I_{12} &= L_{11}K_{12} + L_{12}K_{22} \\ {}_{21} &= L_{22}K_{12} + L_{12}K_{11} \\ I_{22} &= L_{22}K_{22} + L_{12}K_{12} \end{aligned}\right\} \quad (3)$$

Then eq 2 may be written as

$$\left.\begin{aligned} \left(I_{11}\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2}\right)e_1 + I_{12}\frac{\partial^2 e_2}{\partial t^2} &= 0 \\ I_{21}\frac{\partial^2 e_1}{\partial t^2} + \left(I_{22}\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2}\right)e_2 &= 0 \end{aligned}\right\} \quad (4)$$

Assume that eq 4 is satisfied by wave solutions

$$\left.\begin{aligned} e_1 &= f(x + vt) \\ e_2 &= g(x + vt) \end{aligned}\right\} \quad (5)$$

Substituting eq 5 in eq 4

$$\left.\begin{aligned}(I_{11}v^2 - 1)\, f''(x + vt) + I_{12}v^2 g''(x + vt) &= 0\\ I_{21}v^2 f''(x + vt) + (I_{22}v^2 - 1)\, g''(x + vt) &= 0\end{aligned}\right\} \quad (6)$$

Integrating each term of eq 6 twice with respect to x, the following relationships are seen to exist

$$g(x + vt) = \left(\frac{1 - v^2 I_{11}}{v^2 I_{12}}\right) f(x + vt) = af(x + vt) \quad (7)$$

$$v^{-4} - (I_{11} + I_{22})\, v^{-2} + (I_{11}I_{22} - I_{12}I_{21}) = 0 \quad (8)$$

Hence by eq 8

$$\frac{1}{v} = \pm\sqrt{\frac{(I_{11} + I_{22})}{2} \pm \frac{1}{2}\sqrt{(I_{11} - I_{22})^2 + 4\, I_{12}I_{21}}} \quad (9)$$

Corresponding to the interior ($\pm$) sign there are 2 numerically different values for the velocity v, and according to the exterior ($\pm$) sign the waves having these velocities may be either forward or backward moving waves. Moreover, by eq 7 waves on the 2 conductors having like velocities are definitely related. Therefore, calling the 2 velocities v_1 and v_2 the complete solution for forward waves may be written

$$\left.\begin{aligned}e_1 &= f_1(x - v_1t) + f_2(x - v_2t)\\ e_2 &= a_1 f_1(x - v_1t) + a_2 f_2(x - v_2t)\end{aligned}\right\} \quad (10)$$

and from eq 1 the current waves are

$$\left.\begin{aligned}i_1 &= (K_{11} + a_1K_{12})v_1 f_1(x - v_1t) + (K_{11} + a_2K_{12})v_2 f_2(x - v_2t)\\ i_2 &= (K_{12} + a_1K_{22})v_1 f_1(x - v_1t) + (K_{12} + a_2K_{22})v_2 f_2(x - v_2t)\end{aligned}\right\} \quad (11)$$

where

$$\left.\begin{aligned}a_1 &= \left(\frac{1 - v_1^2 I_{11}}{v_1^2 I_{12}}\right)\\ a_2 &= \left(\frac{1 - v_2^2 I_{11}}{v_2^2 I_{12}}\right)\end{aligned}\right\} \quad (12)$$

From eq 10 and eq 11 the effective coupling may be determined. Fig. 7 shows a wave being impressed on one wire of a 2-conductor circuit. Obviously there can be no current initially on the isolated conductor, so that at $t = 0$, eq 11 gives

$$f_2(x) = -\left(\frac{K_{12} + a_1K_{22}}{K_{12} + a_2K_{22}}\right)\frac{v_1}{v_2} f_1(x) = -wf_1(x) \quad (13)$$

This equation shows that the 2 waves have the same shape, but differ in magnitude. Hence for this case eq 10 becomes

$$\left.\begin{aligned}e_1 &= f_1(x - v_1t) - wf_1(x - v_2t)\\ e_2 &= a_1 f_1(x - v_1t) - wa_2 f_1(x - v_2t)\end{aligned}\right\} \quad (14)$$

Now if the initial wave impressed on the bottom conductor at $t = 0$ is $e_1 = E(x)$ then eq 14 gives

$$E(x) = f_1(x) - wf_1(x) \quad (15)$$

hence

$$f_1(x) = \frac{E(x)}{1 - w} \quad (16)$$

and finally

$$\left.\begin{aligned}e_1 &= \frac{1}{1 - w}E(x - v_1t) - \frac{w}{1 - w}E(x - v_2t)\\ e_2 &= \frac{a_1}{1 - w}E(x - v_1t) - \frac{a_2w}{1 - w}E(x - v_2t)\end{aligned}\right\} \quad (17)$$

Thus 2 waves with different velocities but of the same shape (in space) are present on both conductors. If the initial wave is impressed as a function of time $E(t)$ at $x = 0$, then eq 17 must be remodeled as follows:

$$\left.\begin{aligned}e_1 &= \frac{1}{1 - w}E\left(t - \frac{x}{v_1}\right) - \frac{w}{1 - w}E\left(t - \frac{x}{v_2}\right)\\ e_2 &= \frac{a_1}{1 - w}E\left(t - \frac{x}{v_1}\right) - \frac{a_2w}{1 - w}E\left(t - \frac{x}{v_2}\right)\end{aligned}\right\} \quad (18)$$

In this case the waves have the same duration as time functions, but are of different lengths and moving at different velocities. They start out together but the faster wave runs ahead and distortion results. For instance, suppose that the 2 waves of e_2 are of opposite polarity and that the negative polarity is the faster and smaller component. Then initially e_2 appears as a complete positive polarity wave, but after a while the negative component has forged ahead where it is no longer nullified, and e_2 then appears more elongated with a negative loop in front, and the main crest hardly at all affected by attenuation, because the negative component is partially detached and therefore does not subtract as much from the positive crest. These possibilities are demonstrated in the text by numerical examples and compared with actual impulse tests on transmission lines.

The more general analysis, applying to an n-conductor system is given in Appendix II.

Appendix II—N-Conductor System

The voltage waves (e_1, e_2, ..., e_n) on an n-wire multi-conductor system with zero losses are related by the following set of simultaneous differential equations (see chapter VI of reference 6):

$$\left.\begin{aligned}0 &= A_{11}e_1 + J_{12}e_2 + \ldots\ldots + J_{1n}e_n\\ 0 &= J_{21}e_1 + A_{22}e_2 + \ldots\ldots + J_{2n}e_n\\ &\ldots\ldots\ldots\ldots\ldots\ldots\\ 0 &= J_{n1}e_1 + J_{n2}e_2 + \ldots\ldots + A_{nn}e_n\end{aligned}\right\} \quad (1)$$

in which

$$J_{rs} = (L_{1r}K_{1s} + L_{2r}K_{2s} + \ldots + L_{nr}K_{ns})\frac{\partial^2}{\partial t^2} = I_{rs}\frac{\partial^2}{\partial t^2} \quad (2)$$

$$A_{rr} = \left(I_{rr}\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2}\right) \quad (3)$$

It has been shown (see chapter VI of reference 6) that these equations are satisfied by wave solutions

$$e = f(x \pm vt) \quad (4)$$

and that there are in general n distinct waves on each conductor. Each wave has a different velocity of propagation, as given by the roots of the following matrix:

$$\left.\begin{vmatrix}B_{11}I_{12} \ldots\ldots I_{1n}\\ I_{21}B_{22} \ldots\ldots I_{2n}\\ \ldots\ldots\ldots\ldots\\ I_{n1}I_{n2} \ldots\ldots B_{nn}\end{vmatrix} = 0\right. \quad (5)$$

where

$$B_{rr} = (I_{rr} - v^{-2}) \quad (6)$$

Thus there can exist simultaneously on each conductor of an n-conductor system n pairs of traveling waves of different velocities of propagation (v_1, v_2, ..., v_n) and each pair consists of a forward and backward wave. Therefore

$$\left.\begin{aligned}e_1 &= [f_{11}(x - v_1t) + F_{11}(x + v_1t)] + \ldots\ldots\ldots\ldots +\\ &\qquad [f_{1n}(x - v_nt) + F_{1n}(x + v_nt)]\\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\\ e_n &= [f_{n1}(x - v_1t) + F_{n1}(x + v_1t)] + \ldots\ldots\ldots\ldots +\\ &\qquad [f_{nn}(x - v_nt) + F_{nn}(x + v_nt)]\end{aligned}\right\} \quad (7)$$

The corresponding currents are given by

$$\left.\begin{aligned}i_1 &= \Sigma\, v_r\,[K_{11}(f_{1r} - F_{1r}) + \ldots\ldots + K_{1n}(f_{nr} - F_{1nr})]\\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\\ i_n &= \Sigma\, v_r\,[K_{n1}(f_{1r} - F_{1r}) + \ldots\ldots + K_{nn}(f_{nr} - F_{nr})]\end{aligned}\right\} \quad (8)$$

If the effective radii and ground planes of the conductors with respect to the capacitance coefficients are the same as for the inductance coefficients, then eq 5 yields but a single value for the velocity of propagation (equal to the velocity of light) and eqs 7 and 8 then have but a single pair of waves on each conductor. But if

the effective radii and ground planes are different for the capacitance coefficients, then the waves with different velocities exist. However, all the waves of eq 7 are not independent. Substituting eq 7 into eq 1 and equating the terms of waves having the same velocity, there result n simultaneous equations relating the n waves having like velocities, from which any $(n-1)$ of them may be eliminated. Equation 7 may then be rewritten as

$$\left.\begin{aligned} e_1 &= a_{11}\,[f_1(x-v_1t)+F_1(x+v_1t)]+\ldots\ldots+a_{1n}\\ &\qquad [f_n(x-v_nt)+F_n(x+v_nt)]\\ e_2 &= a_{21}\,[f_1(x-v_1t)+F_1(x+v_1t)]+\ldots\ldots+a_{2n}\\ &\qquad [f_n(x-v_nt)+F_n(x+v_nt)]\\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\\ e_n &= a_{n1}\,[f_1(x-v_1t)+F_1(x+v_1t)]+\ldots\ldots+a_{nn}\\ &\qquad [f_n(x-v_nt)+F_n(x+v_nt)] \end{aligned}\right\} \quad (9)$$

where the a coefficients are the proportionality factors between waves with the same velocity, as determined by substituting eq 9 in eq 1 and equating the coefficients of waves with like velocities. The current equations (eq 8) simplify to

$$\left.\begin{aligned} i_1 &= \Sigma\,(K_{11}a_{1r}+K_{12}a_{2r}+\ldots.+K_{1n}a_{nr})\,v_r\,(f_r-F_r)\\ i_2 &= \Sigma\,(K_{21}a_{1r}+K_{22}a_{2r}+\ldots.+K_{2n}a_{nr})\,v_r\,(f_r-F_r)\\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\\ i_3 &= \Sigma\,(K_{n1}a_{1r}+K_{n2}a_{2r}+\ldots.+K_{nn}a_{nr})\,v_r\,(f_r-F_r) \end{aligned}\right\} \quad (10)$$

These, then, are the general equations of traveling waves on a no-loss multi-conductor system. The $2n$ remaining forward and backward waves are determined from the terminal or initial conditions.

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Simultaneous Control of Voltage and Power Factor

By L. F. BLUME, ASSOCIATE A.I.E.E. and F. L. WOODS, APPLICATION PENDING

Both of the General Electric Company, Pittsfield, Mass.

A method of maintaining constant voltage at the load center of a transmission system, utilizing load ratio control equipment in combination with fixed capacitors, is described in this paper. This method combines the desirable performance characteristics of both the synchronous condenser and load ratio control methods, and in some cases results in appreciable savings in overall system losses.

MAINTENANCE of constant voltage at the receiving bus or load center of a transmission system, independently of wide fluctuations in load, may be accomplished either by means of a synchronous condenser or by the introduction of voltage control apparatus at some convenient point, such as induction regulators or load ratio control.

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The former method maintains constant voltage at the receiving bus, by adjusting line power factor so that line drop between receiving and sending busses remains constant for all loads. The latter method permits line drop to vary with load, but nevertheless maintains constant voltage on the receiving bus by inserting in the system a variable compensating voltage.

Although the 2 methods are radically different in principle, they both are being used extensively. In this paper the essential characteristics of the 2 methods are compared theoretically, primarily for the purpose of indicating how a third method, consisting of the combination of load ratio control and capacitors, may combine advantageously the desirable performance characteristics of the synchronous condenser and load ratio control.

It is shown that: (1) with the use of the combination equipment, appreciable savings in over-all system losses, both at no load and at full load, may be expected in some cases, as compared with either the synchronous condenser or load ratio control; (2) the capacitive kilovoltamperes required in the combination equipment is much less than when the

synchronous condenser is used; and (3) the transformer tap range is less than when standard load ratio control is used. The conclusion is reached that the combination equipment is superior under the following conditions: (1) the increased kilovoltamperes made available to the system by the use of the synchronous condenser is not of sufficient value to justify the extra cost involved; (2) where the advantages inherent in the synchronous condenser by virtue of its being a rotating device are not important; and (3) where the economies resulting from power factor correction justify the increase in first cost as compared with standard load ratio control. In view of the advantages inherently possessed by the combination equipment, obviously there are many practical situations in which this method is to be recommended.

Description of the "Combination Method"

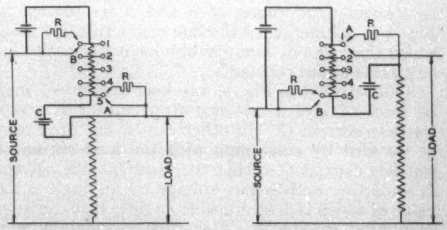
A bank of static capacitors may be so interconnected with a tap changing transformer that the capacitive kilovoltamperes introduced into the circuit is a function of the tap on which the transformer is operating and hence of the load. Figure 1 is the connection diagram of one arrangement, showing an autotransformer with taps in the series winding. By means of contacts A and B the incoming and outgoing lines may be connected to any of the taps; A and B are moved alternately and in opposite directions by means of a standard load-ratio-control mechanism. The position of the contacts shown in Fig. 1 (A on tap 5 and B on tap 1) correspond to maximum buck, in general the no load operating position. In the other extreme position, i. e., maximum boost position, contact A will be on tap 1, and contact B on tap 5 (Fig. 2) corresponding in general to the full load condition. Capacitors C are connected between the series and common windings in such a manner that in the maximum buck position, the voltage across them is zero, while in the maximum boost position, they receive the full voltage of the series winding. Thus, it is evident that at light loads, at which the equipment will be operating at or near its maximum buck position, no leading current will be introduced into the lines. Conversely, at full load, at which the equipment will be operating at or near its maximum boost position, maximum leading current will be introduced into the lines.

By this means, the output voltage can be maintained constant automatically, either at the transformer terminals or at the load center (with the aid of line-drop compensators); and simultaneously, leading current can be introduced into the circuit roughly proportional to the amount of load.

This combination scheme of control has characteristics similar to the synchronous condenser in that increasing leading kilovoltamperes are thrown on the system with increasing load, and at the same time voltage is held constant at the receiver bus. It differs fundamentally from a synchronous condenser in that voltage control is obtained by changing transformer ratio, as well as by changing the leading kilovoltamperes, whereas with the synchronous condenser, voltage control is obtained solely by controlling the amount of reactive kilovoltamperes, leading or lagging, that the condenser introduces into the system. On this account, especially if the synchronous condenser is used for maintaining constant voltage under all load conditions, the resultant power factor will not always be the most desirable. This is especially evident at light loads, under which condition the synchronous condenser is made to circulate lagging reactive kilovoltamperes in the system to prevent excessive voltage from appearing on the receiving bus. Therefore, the combination scheme of control, using variable transformer ratio, together with variable reactive kilovoltamperes, provides, from this point of view, a superior method of holding constant voltage. Furthermore, the kilovoltampere rating of the synchronous condenser for a given condition may be appreciably greater than the maximum leading kilovoltampere rating of the load ratio power factor control, because the former rating depends not only upon the economical power factor at which the system should operate at full load, but also upon the requirements of maintaining voltage constant. Thus it is found, in the example to be discussed, that the leading kilovoltampere rating of the synchronous condenser is about twice the capacitor rating for similar performance.

Elementary Considerations

In order to obtain a simple and direct comparison of the performance characteristics of the different methods, a simple one-way transmission system, equipped in turn with the 3 types of control, will be considered. As an aid to this comparison, it is convenient to use for reference purposes, that current



Maximum "buck" position; minimum voltage across capacitor

Maximum "boost" position; maximum voltage across capacitor

Figs. 1 (left) and 2 (right). Connections of equipment used for load-ratio power-factor control

which may flow through the line without producing any line drop between sending and receiving busses. This *zero-line-drop current* may have any magnitude whatever, but for any particular magnitude its phase angle is determined strictly by the impedance characteristics of the line. It must lead the receiving bus voltage by an angle ϕ (see tabulated list for definition of all symbols) the value of which

may be determined geometrically from the vector diagram, Fig. 3. Under these conditions, the sending and receiving bus voltages E_0 E_R form an isosceles triangle, the base of which is the impedance volts. From this diagram, the angle ϕ by which the zero-line-drop current I_0 leads the receiving bus voltage can be determined readily for any value of transmission line impedance. The angle ϕ can be considered to be made up of the sum of 2 angles, α which is a function of the impedance volts, and β which is a function of the ratio of line reactance to line resistance. The values of α and β are plotted in Fig. 4 as a function of the line characteristics, from which the value of ϕ can be obtained very easily for any value of line constants.

Definition of Symbols

α	= an angle depending on the per cent line impedance
β	= an angle depending on the ratio X/R
ϕ	= $\alpha + \beta$
θ	= power factor angle
θ'	= corrected power factor angle
E_0	= sending end voltage
E_R	= receiving bus voltage
I_0	= zero-line-drop current
I_L	= load current referred to the line
I_L'	= load current referred to the line after power factor has been corrected
Z	= impedance of circuit, including line, transformers, etc., all of which hereafter are referred to as line, expressed in per cent
X	= reactive component of Z
R	= resistance component of Z
Q	= quadrature current to be added to I_L to give I_0
Q_1	= component of Q due to load power factor
Q_2	= component of Q due to line constants
Q_3	= leading quadrature current introduced for power factor correction
Q_4	= quadrature current causing line drop
r	= turn ratio of load ratio control transformer in maximum boost position

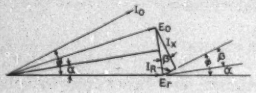


Fig. 3. Vector diagram showing zero-line-drop current

See tabulated list for definition of symbols

As illustrated in Fig. 5, any load current I_L may be resolved into a zero-line-drop current I_0 and a wattless current Q. In other words, line drop may be avoided by combining with the load current a wattless current Q so that the resultant line current I_0 leads the receiver bus voltage by an angle ϕ the value of which is determined from line characteristics as plotted in Fig. 4. This current diagram may vary in value from maximum to zero without introducing line drop or regulation, provided the proper power factor of the line current for zero line-drop always is maintained.

Synchronous Condenser. If, instead of providing the quadrature current Q necessary to maintain the zero-line-drop current, a quadrature current Q_3 (Fig. 6) is added giving a resulting line current I_L', then a line drop is introduced the value of which is determined by Q_4, which is the vector difference between I_L' and I_0. The numerical value of the line drop is equal to Q_4 times the line reactance X. The current Q_4 is necessarily constant to satisfy the condition of constant terminal voltage, taking for granted that the synchronous condenser is operating to maintain constant voltage at the receiving bus for all loads. It is, therefore, independent of load and may be designated as the *line-drop current.* Being constant and independent of the load, it is the lagging current supplied to the line by the synchronous condenser at no load.

Although both current diagrams, Figs. 5 and 6, are applicable to any value of load, their particular usefulness, as far as the present purpose of the paper is concerned, lies in the fact that from them the full load rating of the voltage control equipment may be determined quickly and accurately. For this purpose assume that the current I_L is the rated full load current for which the system is to be designed. Then the value of Q determines the synchronous condenser rating.

Generally, a synchronous condenser is designed to deliver 50 per cent lagging current at no load, in which case the full load leading output is $^2/_3Q$, the no load output is $^1/_3Q$, and the line drop becomes $^1/_3QX$.

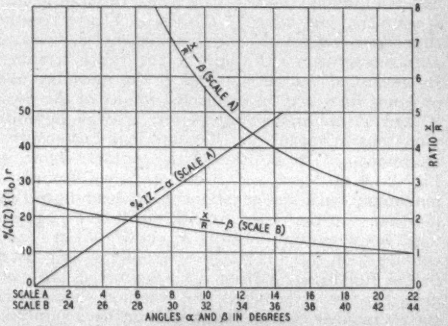


Fig. 4. Curves for determining angles α and β from circuit constants

By the foregoing procedure the currents concerned with the operation of the synchronous condenser have been analyzed into the variable current triangle, consisting of I_L, I_0, and Q, and the constant current Q_4, which determines line drop. The actual current flowing in the condenser, as well as in the system, is determined for both rated load and fractional load by the vector resultant of the variable and constant currents. Thus, assuming that Fig. 6 represents the rated load conditions, then rated current flowing in the line is represented by I_L' and the rated leading current of the synchronous condenser is Q_3. For fractional loads the variable currents are reduced porportionally, but the constant current Q_4 remains unchanged. Thus at 50-per cent load, the resultant currents are illustrated in Fig. 6 *A;* and at no load the current triangle vanishes leaving the constant current Q_4 as the only current flowing in the system.

Load Ratio Control. In this case, the load current I_L is also the line current, and the resulting line

regulation (which is measured by Q, the amount of departure from zero-line-drop current) is neutralized by introducing a compensating voltage, thus holding the receiving bus voltage constant. The total line drop is QrX where r is the turn ratio in the maximum boost position of the regulating transformer. Assuming equal buck and boost range, the load ratio control range becomes $\pm QrX/2$, and the maximum ratio r of the regulating transformer is

$$r = 1 + \frac{QrX}{2} = \frac{2}{2 - QX}$$

which determines the required ratio of the regulating transformer.

Combination Scheme With Capacitor. In the combination of load ratio control with capacitors, we may assume that at full load the capacitors with maximum load ratio control range impressed across them, furnish a leading current Q_3, Fig. 7, sufficient to correct the line power factor to a specified value, say 95 per cent.

The amount of departure of the line current I_L' from the zero-line-drop current is Q_4 and the total line drop is Q_4rX where r is the turn ratio in the maximum boost position of the regulating transformer. Assuming equal buck and boost range, the load ratio control range becomes $Q_4rX/2$, and

$$r = 1 + \frac{Q_4rX}{2} = \frac{2}{2 - Q_4X}$$

which determines the required ratio of the regulating transformer.

Use of Chart

To facilitate the evaluation of Q, a chart (Fig. 8) has been prepared, from which the values of Q_1 and Q_2 for any value of ϕ and any condition of load may be readily determined directly. To illustrate the use of the chart, assume for example, a 3-phase circuit having the following characteristics:

Total line impedance including step-up and step-down transformers ($\%IZ$)	20%
Ratio of line reactance to resistance (X/R)	6
Rated load delivered at receiving bus	100%
Power factor of load	80%
Receiving bus voltage	100%

For 100-per cent load at 80-per cent power factor, zero-line-drop current as determined from the chart is 83 per cent. (Only by successive trials can this value be determined accurately since it is affected by the value of ϕ.) Determine by means of Fig. 4 the angle ϕ, by which the zero-line-drop current leads the receiving bus voltage.

$(\%IZ)\ I_0 = 0.20 \times 0.83 = 0.166$ Hence $\alpha = 4.6°$
$X/R = 6$ $\beta = 9.4°$
$\alpha + \beta = 14.0°$

By means of the chart, Fig. 8, the numerical value of the quadrature current Q is determined (Fig. 5) for $\phi = 14°$ and load power 80 per cent, this being made up of $Q_1 + Q_2$, obtained from the chart. Thus

$Q_2 = 20\%$
$Q_1 = 60\%$
$Q = 80\%$

from which the required ratings of the various control equipments can be determined quickly, as previously described.

Where a synchronous condenser having a 50-per cent lagging rating is used, the size of the condenser is $^2/_3Q = 53$ per cent; for full load this corrects the 80-per cent power factor load to $60 - 53 = 7$ per

Table I—Performance Characteristics of the 3 Equipments

Constant voltage maintained under the following conditions: load power factor = 80 per cent; line impedance = 20 per cent; $X/R = 6$; $X = 19.7$ per cent

		Synchronous Condenser	Load Ratio-Power Factor Control	Load Ratio Control
	Full Load Performance			
1.	Load	100%	100%	100%
2.	Load power factor	80%	80%	80%
3.	Line power factor	99.5%	95%	80%
4.	Line impedance	20%	20%	20%
5.	X/R	6	6	6
6.	X	19.7%	19.7%	19.7%
7.	Q, obtained from chart	80%	80%	80%
8.	Leading current introduced	53%	34%	0%
9.	Lagging current effective in producing line drop	27%	46%	80%
10.	Line drop	5.31%	9.50%	17.1%
11.	Line current	80%	87.1%	108.5%
12.	Voltage boost	0%	4.75%	8.55%
	Comparative losses:			
13.	Voltage control apparatus	38	5.3	5.3
14.	Line and transformers	62	78	118
15.	Total system losses	100	83.3	123.3
	No Load Performance			
16.	Line current	28%	0	0
17.	Line drop	5.5%	0	0
18.	Voltage buck	0	−4.75%	−8.55%
	Comparative losses:			
19.	Voltage control apparatus	26.8	1.1	1.1
20.	Line and transformers	15.2	13.4	14.4
21.	Total system losses	42.0	14.5	15.5

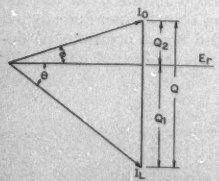


Fig. 5. Vector diagram of variable currents

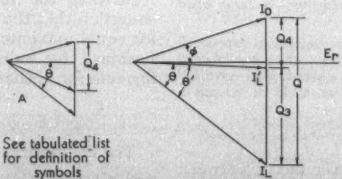


Fig. 6. Vector diagram for a synchronous condenser with 50-per cent lagging rating ($Q_4 = \frac{1}{2}\ Q_3$)

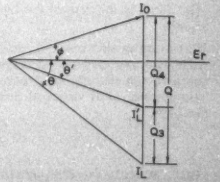


Fig. 7. Vector diagram for load-ratio power-factor control

Fig. 8. Chart for determining rating of control equipment; broken line shows a concrete example of the following procedure:

1. Locate intersection of given load power factor radius with load current arc in the lower half of the chart

2. Project this intersection horizontally and note on the vertical quadrature current scale the quadrature current Q_1 in per cent of load current

3. From Fig. 4 determine values of ϕ equal to $\alpha + \beta$ (the phase angle of the zero-line-drop current) assuming both I_0 and r equal to unity

4. Draw a radius in upper half of chart from origin corresponding to the value of angle ϕ

5. The intersection of the radius just determined with the vertical line drawn through the intersection as determined in (1) gives the magnitude of zero-line-drop current. Its value can be read directly by means of the circular arcs

6. Project the intersection as determined in the preceding paragraph horizontally and read the corresponding value Q_2 on the vertical quadrature current scale

SYNCHRONOUS CONDENSER. Adding the values obtained in (2) and (6) gives $Q = Q_1 + Q_2$, which is the combined leading plus lagging rating of the synchronous condenser expressed in per cent of the assumed load current

LOAD RATIO CONTROL. Maximum ratio of load ratio control equipment necessary to compensate for the line regulation is obtained by substituting in equation $r = \frac{2}{2 - QX}$

COMBINATION EQUIPMENT. When capacitors are added to load ratio control equipment, first determine zero-line-drop current in the same manner as described in (1) to (6) and in addition proceed as follows:

7. Project the intersection as determined in (2) vertically until it meets the radial power factor line corresponding to the power factor to which it is desired to correct, and project this intersection horizontally to the vertical quadrature scale and note its value

8. Subtract this value from the value obtained in (2) to give the current rating of the capacitors (in per cent of assumed full load) required to obtain the desired power factor correction

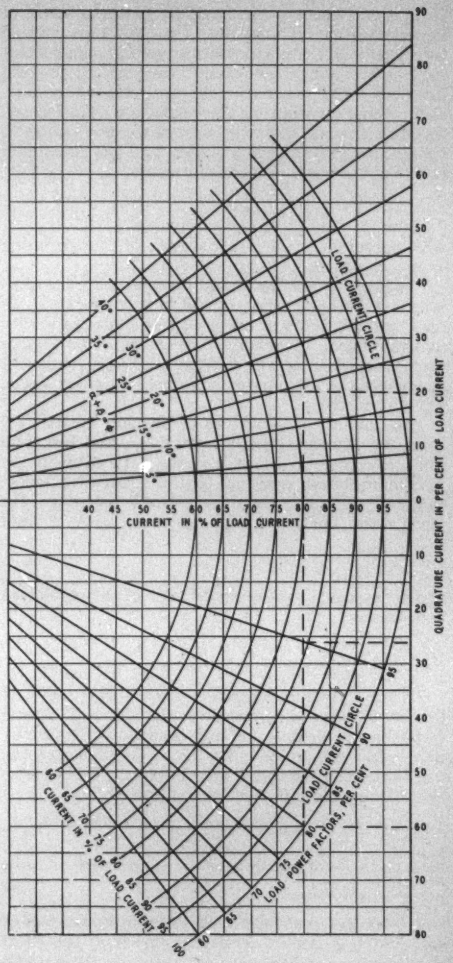
9. Add the value obtained in (9) to the value of Q_1 obtained in (2) to obtain the quadrature current Q_4

10. The maximum ratio of regulating transformer necessary to compensate for the line regulation is obtained by substituting in equation $r = \frac{2}{2 - Q_4X}$

PROCEDURE FOR GREATER ACCURACY. In the above procedure a small error is introduced because in obtaining α and ϕ both I_0 and r are assumed to be equal to unity. This assumption gives values of α and ϕ slightly larger than the correct values, and therefore the equipment ratings so determined are greater than the real values. To correct this error, proceed as follows:

11. Multiply the per cent line impedance by the values of zero-line-drop current and r as obtained above, and use this value in redetermining ϕ. With the new value of ϕ repeat the procedure starting from (4). Note in the case of the synchronous condenser r is always equal to unity

12. In using this chart, it will be found convenient to express all voltages in per cent of the receiving bus voltage which is maintained constant, and all currents in per cent of the assumed uncorrected full load current. All values of line characteristics should be reduced to this base.



cent, which corresponds to a power factor between 99.75 per cent and unity. The lagging rating $\frac{1}{8}Q$ = 27 per cent multiplied by line reactance 19.7 per cent determines the line drop; $0.27 \times 0.197 = 0.053$ or 5.31 per cent.

Where load ratio control is used to neutralize line regulation, the maximum ratio required on the assumption that the regulating transformer is designed for equal maximum buck and boost positions, is determined by substituting the value of Q in the formula for r, that is

$$r = \frac{2}{2 - QX} = \frac{2}{2 - (0.80 \times 0.197)} = 1.083$$

The line drop is then

$$0.80 \times 1.083 \times 0.197 = 0.171 \text{ or } 17.1\%$$

Where load ratio-power factor control is used, assume that in the full boost position the capacitive kilovoltamperes introduced is sufficient to improve

the power factor from 80 per cent to 95 per cent. The corresponding leading current Q_3 (Fig. 7) as obtained from the chart is 0.64 − 0.28 = 0.36. The amount of departure of the line current I_L' from the zero-line-drop current is equal to

$$Q_4 = Q - Q_3 = 80 - 36 = 46\%$$

The maximum ratio required for the regulating transformer on the assumption that it is designed for equal maximum buck and boost positions, is determined by substituting the value of Q_4 in the formula for r, that is

$$r = \frac{2}{2 - Q_4 X} = \frac{2}{2 - (0.46 \times 0.197)} = 1.05$$

The total line drop is

$$Q_4 X = 0.46 \times 1.05 \times 0.197 = 0.095 \text{ or } 9.5\%$$

A comparative study of the operating characteristics of the 3 types of equipments was made in the manner just described for a typical one-way transmission system involving a step-up and step-down transformer, and on the assumption that constant voltage is maintained under all conditions on both the sending and receiving busses. The results of this study are given in Table I.

Comparison of the 3 Methods

Table I illustrates the appreciable saving in losses made possible by the use of the combination equipment, due to its inherently higher efficiency as compared with the synchronous condenser. The total system losses are less, in spite of the fact that for full load on the system the line losses, including the step-up and step-down transformers, are greater (compare items 14 and 15). At no load the total system losses also are appreciably less (item 21).

It follows that for all intermediate loads, the overall system efficiency should be higher, and the total system losses for any load cycle, should be less. In Fig. 9 are plotted loss curves representing the total system losses from no load to full load for a system rated 12,500 kilovoltamperes.

By correcting the line power factor to 95 per cent, the capacitive kilovoltamperes required for the combination equipment become appreciably less than for the synchronous condenser (item 8) and this fact results in major reductions in first cost for the combination equipment. The assumption tacitly is made here that power factor correction to values greater than 95 per cent generally is not desired for economical reasons, and that it is done in the case of the synchronous condenser because of the necessity of maintaining constant voltage. The difference in the effect on the line current is shown in item 11 of Table I. These differences in line currents are due in part to the difference in the power factor of the resulting line currents, and in part to the turn ratio of the regulating transformer, which, in the maximum boost position corresponding to full load, must be introduced to neutralize the line regulation (item 12).

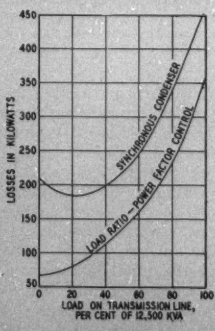


Fig. 9. Comparison of system losses with 2 methods of control

The advantages of minimum line current (item 11) for identical loads, obtained by the use of the synchronous condenser, are obvious, because for a given maximum line current, limited by the current rating of the station equipment, the system is capable of delivering more kilowatts and more kilovoltamperes to the load. The importance of this advantage can be judged only in connection with specific applications, since so much depends upon whether the safe current limits of the system apparatus are approached.

Combination Scheme vs. Load Ratio Control

A general comparison of the advantages of the combination scheme with those of ordinary load ratio control, depends largely on the question of whether for a given application it is economically desirable to improve the line power factor. As the first major cost of the combination equipment consists largely of the capacitor costs, it is obvious that power factor correction must be highly desirable to make the additional cost worthwhile. In the example cited in Table I, the large increase in efficiency and the large reduction in line current resulting from the addition of capacitors, is so great as to justify a considerable increase in the first cost of the control equipment, as compared with load ratio control.

In general, the desirability of combining load ratio control with capacitors, is made less (1) the higher the power factor of the load, and (2) the lower the reactance between the sending and receiver busses. The latter factor, by reducing the transformer tap range necessary to maintain constant voltage, is effective in reducing the first cost of the load ratio control equipment.

Other Advantages of the Combination Scheme

1. The absence of high speed rotating parts, and the fact that practically no auxiliary equipment is required, makes it possible to install the combination equipments at any convenient point on the line.

2. It becomes possible to use several relatively small units and place them on the system closer to the load centers.

3. On account of the ease with which capacitor units may be added when needed, it is not necessary to install at any given time any greater capacity than actually is needed. The rating of the transformer can be made adequate for future growth, but as the cost of capacitors make up the largest part of the total cost, the initial investment is not increased greatly by the necessity for future load growth.

Joint Use of Poles With 6,900-Volt Lines

A plan has been developed for joint occupancy of poles by power and telephone circuits in the Staten Island, N. Y., area, involving 6,900-volt distribution. The aim of this plan is to secure to the public and to the power and telephone companies overall safety, convenience, and economy. Results of this coöperative study of joint use are presented in this paper.

By
W. R. BULLARD, MEMBER A.I.E.E. — Elec. Bond and Share Co., New York, N. Y.
D. H. KEYES, ASSOCIATE A.I.E.E. — Am. Tel. and Tel. Co., New York, N. Y.

Abstract

JOINT use of poles has been found mutually advantageous for the distribution of power and telephone services and coöperative work for the purpose of determining mutually satisfactory practices has been carried on for many years. "Principles and Practices for the Joint Use of Wood Poles" were approved in 1926 by the National Electric Light Association and the Bell Telephone System. At that time, it was found necessary to place some limitations on the joint practices. In order to obtain fully acceptable joint practices, the Joint Subcommittee on Development and Research[1] has carried on a number of studies of the problems in specific areas. The study described in this paper was made for Staten Island, New York, and was concerned with the economics and relative safety of certain phases of power and telephone distribution. The study covers estimated plant requirements for the period from 1932 to 1950, and is based upon estimates of growth of population and service requirements through this period.

Previous studies made by the power company indicated the desirability of supplying the load either by extending the existing 2,300-volt delta system or by changing to a 6,900-volt delta system. Factors which influence the effects which may be experienced in event of contact between the power and telephone circuits are given and evaluated for the particular situation.

The study indicates that in view of conditions which exist in Staten Island and features which would be incorporated in the design and operation of the 6,900-volt system, the safety of joint construction at the higher voltage can be made comparable with that of the 2,300-volt joint construction now existing. The study also shows that substantial economies would be obtained by the use of the 6,900-volt system.

This is an example of the satisfactory solution by coöperative effort of a mutual problem of distribution. The solution arrived at and the conclusions drawn are dependent, as is always the case, upon the local conditions, but the method of attack is felt to be generally applicable to problems of this type.

Full text of a paper recommended for publication by A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 27, 1933; released for publication Nov. 14, 1933. *Not published in pamphlet form.*

1. This work now being carried on jointly by the Edison Electric Institute and the Bell Telephone System.

Introduction

The public requires both power and telephone service, and the problem of distributing these to the same customers involves factors which are so closely interrelated that to arrive at an economically sound solution, coöperative consideration must be given to the requirements of both. In built-up areas where both distribution plants are aerial, joint use of poles in accordance with mutually acceptable practices, is usually preferable to separate pole lines in respect to safety, public relations, and over-all economy.

The problems of joint use of poles received consideration by the Joint General Committee of the National Electric Light Association and Bell Telephone System, and as a result of its early work, that committee published a report dated February 15, 1926, entitled "Principles and Practices for the Joint Use of Wood Poles by Supply and Communication Companies." These principles and practices were intended as a basis on which electric supply companies and communication companies could work out their joint use problems mutually, and among other items, recommend that each party should:

"Be the judge of the quality and requirements of its own service, including the character and design of its own facilities."

"Determine the character of its own circuits and structures to be placed or continued in joint use, and determine the character of the circuits and structures of others with which it will enter into or continue in joint use."

"Coöperate with the other party so that in carrying out the foregoing duties, proper consideration will be given to the mutual problems which may arise and so that the parties can jointly determine the best engineering solution in situations where the facilities of both are involved."

In order to extend this work, the joint subcommittee on development and research is conducting studies of types of plant, methods of construction, and protection practices. Mutually accepted practices for joint use at the lower distribution voltages are well established. However, many of the present day joint use problems relate to the use of higher distribution voltages. These studies include assembly of data to permit the various factors to be weighed, and development of additional or improved methods and devices to meet the present and future requirements. This paper describes briefly the

first of a series of field studies being made in cooperation with operating power and telephone companies. This study was made possible through the coöperation of the New York Telephone Company and the Staten Island Edison Corporation.

Basis of Study

The engineers of the Staten Island Edison Corporation in connection with their system planning had conducted extensive studies of their distribution problem to determine the system that would most economically provide satisfactory electric service. As a result of these studies they determined that either a 6,900-volt delta system or a 2,300-volt delta system would best meet their conditions, the former proving the more economical provided satisfactory joint use of poles could be arranged. Furthermore, local conditions generally make it impracticable to erect more than one pole line on a street. Where such dual lines have been built in the past, it is generally necessary to consolidate them at such time as the poles in either line become defective and require replacement. An exception to this rule is the case of wide streets where it is necessary to place street lighting on both sides. Since mutually acceptable practices for joint use at the higher voltages were not available, the joint subcommittee was invited to coöperate in the study of the overall economies and protection practices applicable to the power and telephone systems, with a view to assisting in finding the best engineering solution for this case.

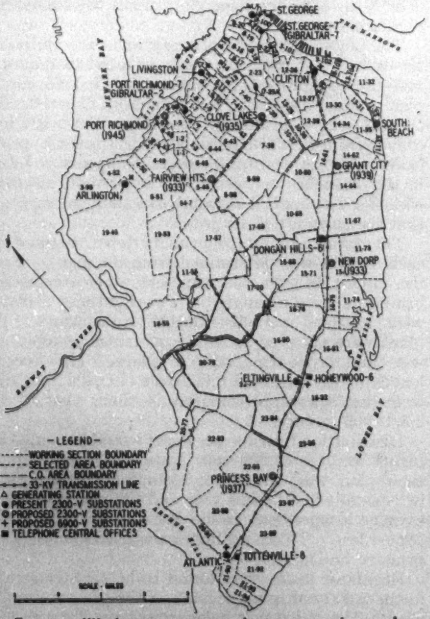


Fig. 1. Working sections, substations, and central offices in Staten Island

General Conditions

Staten Island is 1 of the 5 boroughs of the City of New York. It is located to the southwest of the center of the city and is separated from the New Jersey Coast by a channel averaging about 0.5 mile wide. The island is about 7.5 miles wide and 14 miles long, with an area of about 57 sq miles. Due to the lack of direct transportation to the rest of the City, the development is as yet largely suburban except for a small urban area at the north and a large industrial area along the north and west shores.

The present 2,300-volt joint use plant is of a good average grade of construction. In general, 40-ft poles are used with a span length of 100 ft. The span lengths are largely controlled by local restrictions and street lighting requirements. Joint use has been extensively used throughout the island between telephone circuits and the 2,300-volt circuits.

Power System

At present in Staten Island there are 1 generating station and 6 distribution substations, including 1 at the generating station. The locations of these substations are shown on Fig. 1.

There are now 3 voltages employed in Staten Island—33,000 volts for transmission between the generating station and several of the substations, 6,900 volts for some substation supply but mainly for primary supply to large industries and to a minor extent for other distribution, and 2,300 volts for the remainder of the distribution system throughout the island.

The present distribution transformers are mostly between 5 and 25 kva. They are fused on the primary side for transformer failure, but not for overload. The tendency is to use the 25 to 50-kva sizes and longer secondaries for most cases in new construction. Lightning arresters are used for the protection of all transformers fed from open wire. There are many shade trees on the island, but adequate clearance for the primaries is maintained.

The present substation transformers have 3-section secondary windings which are now connected in parallel for 2,300-volt operation and which can be connected in series for 6,900-volt operation. All of the newer switching gear is suitable for either 2,300-volt or 6,900-volt operation.

The street lighting is a series system using incandescent lamps. Constant current transformers are pole-mounted, supplied from 2,300-volt primary circuits kept separate from the general distribution system.

The power secondaries are generally grounded to the water system on customers' premises.

Telephone System

There are 5 central office buildings on Staten Island, each of which contains a common battery

exchange. The locations of these offices also are given on Fig. 1.

The use of underground cable along main feeder routes is rather extensive, the minimum amount terminated at any one office being 2,000 ft. In general, aerial cables extend from the underground terminals to the limits of each central office area, there being very little open wire. The maximum length of aerial cable is approximately 3 miles, but the average length is materially less.

The many shade trees require the more frequent use of terminals than is the general practice on the aerial cables in order to minimize the number of runs of drop wire along the cables.

Subscribers in the aerial cable territory are served by drop wire between their premises and the aerial cable terminals. Where the drop wire enters a subscriber's premises it is provided with a protector. This protector consists of 7-amp fuses, and carbon block protector gaps from the lines to ground. Telephone protectors are generally grounded to the water system on subscribers' premises.

Growth

The first step in obtaining the requirements for the power and telephone system throughout the period of the study was to arrive at an estimated population growth for the island. Data as to the residence and business development and present usage of the 2 services in the area were studied, together with local and economic factors which were instrumental in effecting past growth or have an influence on the future.

From these factors the number of residence and commercial electric meters was estimated. Taking into account the fact that the power company is promoting electric range and water-heating loads in addition to the other increases in the use of electric power, the load per meter was obtained. A combination of these estimates gives the load for which the distribution system must be designed. The area studies give the distribution of load in various sections of the island.

The telephone study employed the family as a unit and is based upon United States and other census records as to past performance, divided in accordance with the various subdivisions of the study area. The forecast of the future utilization of the telephone was made based on the projection of the various factors and subdivided for the areas.

The detailed methods employed and the results obtained in these growth studies would require more space than could be allotted in this paper.

A section of the island consisting of approximately 13 sq miles, representative of conditions throughout the island, except for a congested underground section, was selected for detailed study. For carrying out the study this selected area was further divided into 14 small working sections.

Power in Selected Area

Maps of the selected area were prepared, showing the location and sizes of all the distribution transformers required to serve the estimated loads. On such a map a layout of primary lines was made for the 6,900-volt plan consisting of 6 feeders radiating from the Eltingville substation. On a similar map the 2,300-volt plan was shown, using 2 substations, 1 at Eltingville with 8 feeders and 1 at New Dorp with 5 feeders. Service requirements and load distribution in this territory make desirable the use of large transformers and extensive secondaries rather than smaller transformers and shorter secondaries. It was recognized that some saving might be effected by using for the 2,300-volt system smaller transformers and less extensive secondaries, but this saving was not considered sufficient to offset the advantages of the large transformers in this territory. Due to these considerations, the assumed locations and sizes of transformers were the same for both voltage systems.

The primary circuits were designed for the same regulation limits in both plans, namely, plus or minus 2 per cent at the load centers and plus or minus 3 per cent at points of maximum variation. Each feeder with its branches was laid out geographically to serve certain distributed loads. The size of wire required between substation and load center to give the desired regulation then was computed. When the specified regulation could not be obtained without going to undesirably large wire sizes, regulators were specified. Sizes larger than No. 4/0 were generally avoided for mechanical reasons, but some larger sizes are now in place and additions were made in certain cases. Single-phase regulators were specified, 2 or 3 on a feeder depending upon the amount of regulation required.

The power loss in the primary wires was estimated for each circuit from the yearly effective load current and the resistance from substation to load center, plus a small allowance for branches. The effective current was determined by comparison with load curves from actual circuits serving similar types of loads and the resistances were computed. Losses in the branches are generally very small since the wire, for mechanical reasons, is usually of such size that the current density is low.

The total amount of primary wire required for each system was determined from the maps. From the circuit lengths the numbers of crossarms and insulators were estimated. Two lightning arresters were assumed per distribution transformer. The plans were made so as to use, as far as possible, the wire and cross-arms now in place. The average length of the assumed 6,900-volt circuits (including branches) was approximately 3 times that of the 2,300-volt circuits.

Distribution transformer losses would be somewhat higher on the 6,900-volt system. The total for each plan was estimated, assuming core losses to be constant for the full year and the effective yearly average copper loss to be 0.2 times the full-load copper loss. This same factor was used in finding the primary line losses.

Regulator losses were found to be slightly greater in the 2,300-volt plan because of the greater number used. The 2,300-volt regulators have 1.6 per cent core loss and 2.4 per cent copper loss at full load as

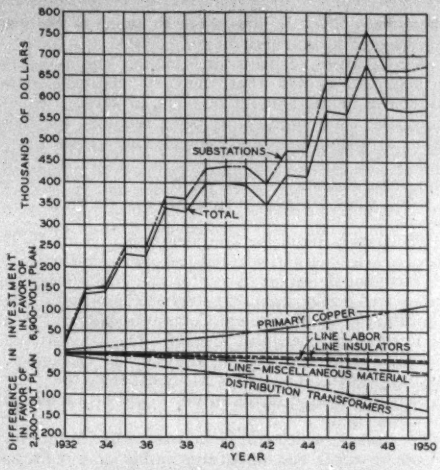


Fig. 2. Difference in investment between 2,300-volt and 6,900-volt plans for the whole Island

compared with 2 per cent core and 3 per cent copper loss in the 6,900-volt regulators. Core losses were assumed constant and copper losses were multiplied by 0.2 as for the transformers.

In both plans the Eltingville substation was used because it is now in operation and there is plenty of room for expanding it. It is necessary to add only the distribution voltage equipment as the present 33-kv equipment is ample. The substation is so located that it will serve some territory outside the selected area.

The 2,300-volt plan requires a new substation at New Dorp. This was necessary since it would be uneconomical to supply the power required for this whole area from Eltingville at 2,300 volts. All equipment for the proposed New Dorp substation was for outdoor mounting to be operated by supervisory control from St. George.

Power System on Whole Island

In order to project the study to include costs of the 2 plans for the whole island, peak loads were calculated for each working section on the island based upon the estimated population at intervals up to 1950. The ratio of load to population at each date was assumed to be the same as in the selected area.

The total line costs were assumed to be in direct proportion to the load served, based upon costs calculated in the selected area. Since additions to the primary system are made in comparatively small units, the investment at any time can be assumed to be proportional to the load served.

The change-over from 2,300 volts to 6,900 volts would require the gradual removal from the system of 2,300-volt transformers, line insulators, and some other equipment. The scrap value of all equipment that was not suitable for use on the 6,900-volt system was credited.

The 6,900-volt plant required no new substations but the total additions to present substations were estimated on the basis of the load requirements in the areas served which were calculated for each year so that the date of installation of additional equipment could be determined. The conversion to 6,900 volts would, of course, be gradual as required by the load growth.

The 2,300-volt plan required 6 new substations by the end of the study period. The dates of installation of new 2,300-volt substations were determined by comparing the cost of feeding a given group of working sections year by year with long feeders and regulators from existing substations against the cost of serving it from a new substation.

The methods used for estimating the losses in the primary wires, distributing transformers, and regulators have been indicated in the study of the selected area. Substation transformer losses were less in the 6,900-volt plan due to the larger sizes of the units, the principal saving being in the core losses. It was found that the increased cost of copper losses in the 2,300-volt substation transformers would be approximately offset by the decreased transmission line losses in the 2,300-volt plan. This difference in transmission loss was due to the tapping off of load at more substations closer together than in the 6,900-volt plan.

Line losses and distribution transformer losses were projected over the whole island and their growth estimated by assuming them to be directly proportional to the load served, based upon the relation between load and losses determined in the selected area. Losses in regulators and substation transformers, however, were added for each unit on the proposed date of its installation.

Table I shows the difference in investment of the various items for the 20-year period. In Fig. 2 is shown the accumulated difference in the capital expenditure year by year.

Table II shows the total difference in power loss in the various parts of the system for the 2 voltages. The accumulated power loss year by year is shown by Fig. 3.

Table I—Net Savings in Investment to 1950

	Favor of 6,900 Volts	Favor of 2,300 Volts
Substations	$674,000	
Primary copper	114,000	
Line insulators		$ 16,500
Line labor		20,000
Distribution trans.		135,000
Miscellaneous		45,500
Total	$788,000	$217,000
Grand total (see item 1 in "Results of Study")	$571,000	

The material and labor costs used were obtained by averaging costs for the period from 1926 to 1931. The present views on slower growth in population and changes which have taken place in costs of labor and material are factors of major importance, and fundamental in the study. These changes would reduce the total savings which the study shows, but should not alter appreciably the percentage difference in cost of the 2 power distribution systems. However, there is a definite indication that when increases are required in the capacity of the distribution substations and feeders on Staten Island, the gradual conversion to the 6,900-volt system in general accordance with the study herein outlined would result in substantial economies.

Table II—Net Savings in Power Loss to 1950

	Favor of 6,900 Volts	Favor of 2,300 Volts
Distribution lines	18,291,000 kwhr	
Substation transformers	14,005,000 kwhr	
Regulators	5,373,000 kwhr	
Distribution trans.		13,651,000 kwhr
Total	37,669,000 kwhr	13,651,000 kwhr
Grand total	24,018,000 kwhr	

Items, on which it was evident that the costs would be approximately the same in both systems, such as power supply, secondaries, customers' services, etc., were omitted from the comparisons.

Pole costs were not included in this study since they would be approximately the same for the 6,900-volt system as for the 2,300-volt system owing to the following:

1. There would be no appreciable difference in the number of poles jointly used because the total length of pole lines from substations to all distribution transformers was approximately the same for the 2 systems.

2. There would be no difference in the height of poles jointly used because the clearance between power and telephone attachments is the same for 6,900 volts as for 2,300 volts.

3. The existing pole sizes meet the strength requirements provided in the National Electrical Safety Code where 6,900-volt joint use is mutually agreed upon.

It was recognized that the costs of operating the 2 systems probably would be different but experience to evaluate this difference was lacking. However, all information available indicated that any increase in operation and maintenance would be small compared to the saving in favor of the 6,900-volt system.

Telephone System in Selected Area

Telephone plant layouts consisting of the aerial cable necessary to serve the estimated number of subscribers in this area were made on maps to the same scale as the power layouts. Two layouts were made for the telephone system to be used with the 6,900-volt power distribution in the selected area; one plan, attaching telephone cables to lines carrying primary wires, as would ordinarily be done with lower voltage primaries, and a second plan, avoiding joint use with primary circuits as far as practicable. There was found to be very little difference in the 2 plans as the power distribution lines had been laid out to avoid telephone routes as far as possible.

The telephone cable layout was superposed on each of the power distribution plans in turn to show the extent of the joint use requirements in the selected area.

Telephone System on Whole Island

This study was extended to cover the whole island by comparing each of the remaining sections with one in the selected area having similar characteristics. The total number of lines in 1950 was estimated for each section and the number of lines requiring protectors was found by assuming that the ratio of these lines to total lines was the same as that in the selected section used for comparison.

A comparison of plans for attaching and avoiding attachment showed that there is relatively little difference in the amount of plant involved. However, the total number of poles required for the latter arrangement would be somewhat greater.

Relative Safety of 2,300- and 6,900-Volt Delta Distribution Systems

The factors requiring consideration in a study of relative safety of various joint use plans are discussed in Provisional Report No. 6 of the Joint Subcommittee on Development and Research, entitled "The Coördination of Power and Communication Systems in Respect to the Joint Use of Poles" (National Electric Light Association Bulletin of December, 1931, p. 815). The plans assumed that the type of plant to be used in the future would be similar to that now used.

The voltage which can be impressed by contact on telephone wires and apparatus inside of buildings, while higher with 6,900 volts than with 2,300 volts, is limited since a favorable relationship between the power and telephone impedances is obtained due to the general use of low resistance grounds for the telephone services on the subscribers' premises.

With either voltage, without coördinative measures, currents as large as 400 amp might continue indefinitely in case of double faults on the power system. If one of these faults should involve the telephone plant, the current would be enough to burn off the cables either at the point of contact or at other locations. The burning off of the cable would eliminate the beneficial effect of the low resistance ground on the sheath and make it possible to impress

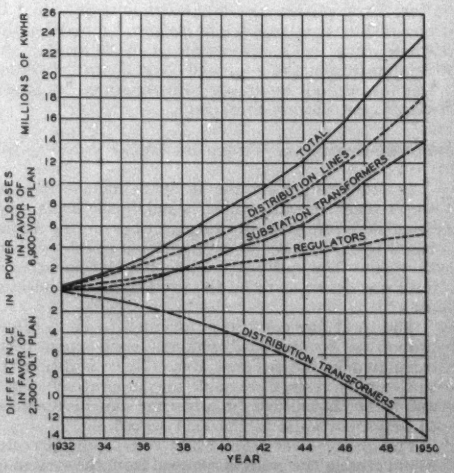


Fig. 3. Difference in power losses between the 2,300-volt and 6,900-volt plans for the whole Island

full phase voltage on drop wire and fuses. Tests and field experience show that the probability of fuses holding over is greater with 6,900 volts impressed than with 2,300 volts. The higher voltages which could be impressed on telephone cable might result in more failures involving many telephone circuits. If a power wire should fall on a drop wire, the insulation of the drop wire under condition of double fault might be subjected to as much as 6,900 volts. This might result in more failures of drop wire insulation than if the voltage were limited to 2,300 volts. A number of typical possible faults involving such a system and telephone plant are illustrated in Table III, and the results indicated.

Based on the above, there is little doubt that if the voltage were raised to 6,900-volts ungrounded delta without additional coördinative measures the hazard of joint use would be increased over that obtaining with 2,300-volts delta. Consideration therefore was directed to finding some practicable means for obviating the increase in hazard.

Separate Pole Lines

Completely separated aerial plants for the 2 utilities would be impossible on account of local conditions and restrictions. In addition, under the conditions in Staten Island, joint poles would usually permit a safer and more satisfactory arrangement of telephone drop and secondary service wires.

Telephone Measures

The protection used at each subscriber station consists of 7-amp fuses (Bell system code 11-*C*) and carbon block protector gaps, of 3-mil spacing (Bell system code Nos. 26 and 27) grounded to the city water system.

Consideration was given to the practicability of obtaining improved safety by using drop wire with heavier insulation and telephone fuses capable of operating properly under higher voltages, provided material and devices and means of applying them were available. This added protection would, of course, have to be applied to all exposed subscriber stations and would not reduce the possible high voltage on the cable or reduce the duration of contacts. Costs for installing these measures, exclusive of material, based upon the number of stations involved were estimated. Estimates of the possible costs of material that would be required were not made.

Power Measures

The use at each substation of a grounding bank of transformers of not less than 15 ohms zero-sequence impedance combined with ground relaying would clear the circuits for faults involving the telephone plant. The sketches of Table IV illustrate several types of fault involving cable and drop wire contacts, and also indicate the possible effects when a grounding bank having 38 ohms zero-sequence impedance is used. The results are based upon certain assumptions as to circuit lengths, grounding conditions, etc., as found in Staten Island and may not apply in other localities. It will be noted from these sketches that:

1. Faults involving telephone plant are quickly cleared, except in some cases when the cross is with the end of a broken wire away from the substation.
2. The voltage which can be impressed on telephone cable is limited to about 1,000 volts.
3. In general, the maximum voltage that can be impressed on drop wire insulation is 4,000 volts.
4. The maximum voltage across a fuse is generally limited to 4,000 volts, but in any case will be less than 6,900 volts.
5. Ground fault currents, in general, will not exceed 300 amp and usually will be cleared in less than 5 sec.

The exact condition which can occur will, of course, be somewhat affected by the impedance of the grounding transformer. Where a grounding bank is used, the circuit will be interrupted promptly by the initial fault to the telephone plant, which largely eliminates the possibility of it being involved in a double fault. Tests as well as field experience show that under the above conditions, the possibility of fuses holding over is not great. In addition to this, with water pipe grounds, the currents resulting, in case of contact, should always be sufficient to clear the circuit in a very short time. In case of contact with cable, the rapid interruption of the circuit will prevent the parting of cable and messenger. This maintains a low impedance through the telephone plant to ground and therefore limits the voltage which can be impressed on the telephone plant.

Design Features

In order to obtain the safety conditions outlined above, the committee considered the following features of construction and design necessary:

1. Construction in accordance with the National Electrical Safety Code.
2. Telephone circuits, except drop loops running from terminals to subscribers' premises, carried in lead sheath cable.
3. Aerial telephone cables bonded to the messengers and to the underground cables.
4. Telephone station grounds of low impedance.
5. The power distribution system grounded through grounding banks with zero-sequence impedance of not less than 15 ohms. These banks to be installed in each 6,900-volt substation and continuously maintained in service to provide neutral point grounding for all feeders.
6. Ground relays installed and continuously maintained in service at such points so that: (1) any primary distribution circuit in case of fault to the telephone plant will be de-energized promptly, and usually within 5 sec; and (2) the current which can flow continuously through the ground connection without relay operation should be kept as small as practicable and not exceeding 100 amp.

Results of Study

A summary of the results of this study follows:

The difference in total investment between the 2,300-volt and 6,900-volt systems at the end of the study period would be about $570,000 in favor of the 6,900-volt system. This difference is influenced by the fact that the pole plant and substation equipment now installed are largely suitable for 6,900-volt operation. In other situations, where extensive replacements of either or both of these items were required substantial difference in relative economy might be expected.

The difference in power losses in favor of the 6,900-volt system would amount to 24,000,000 kwhr by the year 1950.

Table III—Results of Contact Between 6,900-Volt Isolated-Delta Circuit and Telephone Plant

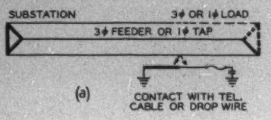
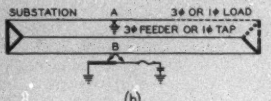
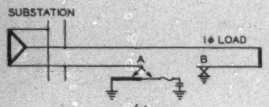
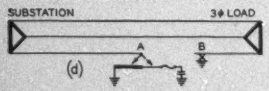
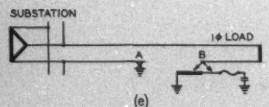
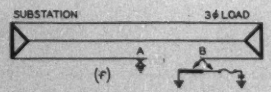
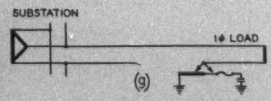
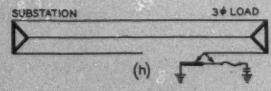
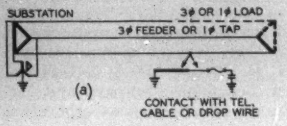
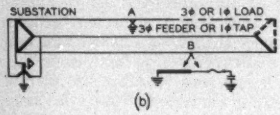
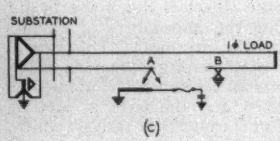
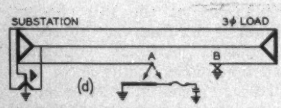
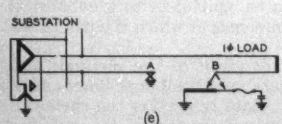
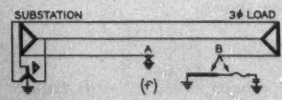
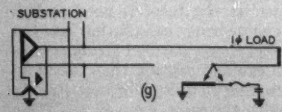
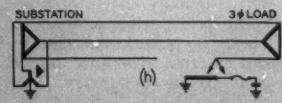
Circuit Diagram	Results of Contact With Cable Sheath or Messenger	Results of Contact With Telephone Drop Wire
 (a)	Fault current less than one amp No relay operation Volts on telephone cable negligible Duration until trouble is cleared The only hazard in this situation would be the removal of wire from contact without proper precautions	Protector blocks operate Fault current less than one amp No relay operation No fuse operation Voltage of telephone loop negligible Duration, until trouble is cleared Voltage available to break down insulation on drop wire, 4,000 volts Only hazard would be removal of wire from contact without proper precautions
 (b)	If total impedance of 2 faults and circuit between them is less than 23 ohms, 300 amp overload relay trips, or less than 17 ohms, 400 amp overload relay trips. (Modified by load current.) Duration, up to several seconds if relay operates; otherwise until trouble is cleared Assuming fault A at bus and B at a distance, with 5 ohms in power circuit and 5 ohms in telephone cable, I = 690 amp, voltage of cable = 3,450 volts Maximum voltage of cable without circuit interruption approximately 2,000 volts (400 amp × 5 ohms) Maximum fault current near substation limited by short-circuit capacity of substation	Protector blocks operate If total impedance of 2 faults and circuit between them is less than 690 ohms, telephone fuse blows, with 6,900 volts across it; or 23 ohms, 300 amp overload relay trips; or 17 ohms, 400 amp overload relay trips. (Modified by load current.) Duration up to several seconds if relay operates; otherwise until trouble is cleared Voltage available to break down insulation on drop wire, 6,900 volts. Maximum current in drop wire about 1,500 amp Maximum voltage 6,900 if not limited by cable, for example, if it burns off and drop wire remains in contact
 (c)	Fault current somewhat less than load current No relay operation Duration, until trouble is cleared As this current can be nearly as great as the load current, without interruption, a poor contact will cause messenger to part and burn sheath and cable conductors. If sheath burns away, 6,900 volts on conductors will cause other cable troubles	Protector blocks operate Fault current somewhat less than load current. Will operate fuse if 10 amp or more. No relay operation Duration, until trouble is cleared Voltage available to break down drop wire insulation 6,900 volts. Volts on drop wire if fuse is not blown, negligible. If fuse operates, maximum voltage across it is 6,900 volts unless limited by cable breakdown
 (d)	Same as above except voltage may be only 6,000 instead of 6,900 if load is balanced	Same as above except voltage may be only 6,000 instead of 6,900 if load is balanced
 (e)	Fault current somewhat less than load current No relay operation Duration, until trouble is cleared As this current can be nearly as great as the load current, without interruption, a poor contact will cause messenger to part and burn sheath and cable conductors. If sheath burns away, 6,900 volts on conductor will cause other cable troubles	Protector blocks operate Fault current somewhat less than load current. Will operate fuse if 10 amp or more. No relay operation Duration, until trouble is cleared Voltage available to break down drop wire insulation, 6,900 volts. Volts on drop wire if fuse is not blown, negligible If fuse operates, maximum voltage across it is 6,900 volts unless limited by cable breakdown
 (f)	Same as above except voltage may be only 6,000 instead of 6,900 if load is balanced	Same as above except voltage may be only 6,000 instead of 6,900 if load is balanced
 (g)	Fault current less than one amp Duration, until trouble is cleared No relay action Voltage of telephone cable, negligible Possible hazard in case of attempt to remove contact without proper precautions	Protector blocks operate Fault current less than one amp Duration, until trouble is cleared Voltage available to break down drop wire insulation, 4,000 volts No relay or fuse action Possible hazard in case of attempt to remove contact without proper precautions
 (h)	Same as above	Same as above

Table IV—Results of Contact Between 6,900-Volt Delta Circuit With Grounding Bank* and Telephone Plant

Circuit Diagram	Results of Contact With Cable Sheath or Messenger	Results of Contact With Telephone Drop Wire
	Fault current up to about 300 amp Relay will clear circuit in less than 5 sec on any cable contact Voltage on telephone cable about 800 volts maximum, for worst impedance conditions in Staten Island. This does not occur with maximum fault current, however Relay operation independent of load	Protector blocks operate Fault current up to about 300 amp Relay will clear circuit in less than 5 sec on any drop wire contact unless fuse clears first Voltage available to break down drop wire insulation, 4,000 volts If fuse operates, maximum voltage across it is 4,000 volts Relay operation independent of load
	If contact at *B* occurs, relay clears in less than 5 sec If contact at *A* occurs first and is less than 70 ohms, it will clear circuit; if greater, fault will remain on until *B* fault occurs Voltage on telephone cable, 800 volts maximum as above Relay operation practically independent of load Maximum current about 300 amp	Protector blocks operate If contact at *B* occurs, relay will clear circuit in less than 5 sec, unless fuse clears first. If contact at *A* occurs first and is less than 70 ohms it will clear circuit, if greater, fault will remain on until *B* fault occurs Voltage available to break down drop wire insulation approximately 4,000 volts Voltage across fuse approximately 4,000 volts Relay operation practically independent of load
	Fault current up to about 300 amp maximum Relay clears circuit in less than 5 sec on contact at *A* Circuit may be cleared by fault *B* if fault impedance is low and if single-phase load beyond *B* is about 650 kva or more Volts on telephone cable about 800 volts maximum as above	Protector blocks operate Fault current up to about 300 amp maximum Relay clears circuit in less than 5 sec on contact at *A* unless fuse clears circuit Circuit may be cleared by fault *B* if fault impedance is low and if single-phase load beyond *B* is about 650 kva or more If fault *B* occurs first, voltage available to break down drop wire insulation, or voltage across fuse after it blows, may be approximately 3,400 to 4,900 volts in case of very large load beyond *B*, but will generally be approximately 4,000 volts
	Same as above, except requires about 1,000 kva 3-phase load to trip circuit through fault at *B*	Same as above, except requires about 1,000 kva 3-phase load to trip circuit through fault at *B*
	Fault current at *B* may reach 50 amp and clear circuit if single-phase load is about 650 kva or more; or current at *A* will clear circuit if impedance is 70 ohms or less Maximum current without tripping, 50 amp Maximum voltage on cable about 250 volts	Protector blocks operate Fault current at *B* may reach 50 amp and clear circuit if single-phase load is about 650 kva or more; or fuse may clear circuit; or current at *A* will clear circuit if impedance is 70 ohms or less Maximum current without tripping, 50 amp Voltage available to break down drop wire insulation, 4,000 volts or more, approaching 6,900 volts as impedance from bus to ground through *A* approaches zero. However, higher voltages remain on for less than 5 sec
	Same as above, except requires about 1,000 kva 3-phase load to trip circuit through fault at *B*	Same as above, except requires about 1,000 kva 3-phase load to trip circuit through fault at *B*, and voltage on drop wire may be from 2,000 to 4,000 volts; or 6,000 to 6,900 volts when impedance at *A* is zero
	Fault current less than 60 per cent of load current previous to fault, and may operate relay if load is 650 kva single-phase or more If load is not sufficient to trip circuit on ground current, fault will remain on	Protector blocks operate Fault current less than 60 per cent of load current previous to fault, and may operate relay if load is 650 kva, single-phase or more; or fuse may clear circuit. Voltage across fuse, 4,000 volts. Voltage to break down drop wire insulation, 4,000 volts
	Fault current less than 1/3 of balanced 3-phase load current; may operate relay if load is about 1,000 kva or more If load is not sufficient to trip circuit on ground current, fault will remain on	Protector blocks operate Fault current less than 1/3 of balanced 3-phase load current; may operate relay if load is about 1,000 kva or more; or fuse may clear circuit Voltage across fuse 2,000–4,000 volts Voltage to break down drop wire insulation 2,000–4,000 volts

* Consisting of 3 transformers rated at 100 kva each; reactance, 38 ohms per transformer. Secondaries connected delta. Ground relay set for minimum tripping current of 50 amp

The cost of the grounding transformers and ground relays for the 6,900-volt distribution system would be about $12,000.

The application to the telephone system of alternative safety measures considered would cost substantially in excess of the cost of the power system measures and does not appear justified in this case. Therefore, the cost of the telephone plant would be about the same in joint use with either power system.

With the additional protective measures provided for the 6,900-volt distribution system, the safety of joint use would compare favorably with that obtained under present conditions.

The adoption of the higher voltage in the power system appears, therefore, to provide the best engineering solution in this case and joint use of facilities apparently may be entered into in all instances in Staten Island where the 2 services should preferably be placed on the same poles.

The joint subcommittee is continuing its studies in other areas since the results of this study are not necessarily applicable where different conditions might influence the results to an important extent.

The authors wish to express their appreciation to the members of their project committee and particularly to Mr. L. F. Fox and Mr. A. A. Williamson of the New York Telephone Company and Mr. J. H. Lytle of the Staten Island Edison Corporation for their assistance and coöperation in carrying out the study upon which this paper is based.

Investigation of Rail Impedances

Measurements of impedance made on 5 sizes of rails and on 2 types of bonds are reported in this paper; the investigation covered a range of current per rail of 20 to 900 amp, and frequencies of 15 to 60 cycles per second. Results are given in a form convenient for engineering use, and include information for applying corrections for bond impedance and for temperature.

By
HOWARD M. TRUEBLOOD
MEMBER A.I.E.E.

GEORGE WASCHECK
NONMEMBER

Both of the American Tel. & Tel. Co., New York, N. Y.

PRINCIPAL results of experimental work, done in 1929 and 1930, to determine impedances of railroad rails over a range of frequencies and currents are given in this paper. The results are divided in a general way into 2 groups: one having to do with certain questions of general interest concerning rail characteristics (Figs. 3 to 8, and Tables I to VI), while in the other the data is presented in convenient form for engineering use (Figs. 9 to 15, and Table VII).

Full text of a paper recommended for publication by the A.I.E.E. committee on transportation, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1933. Manuscript submitted Oct. 10, 1932; released Nov. 9, 1932. *Not published in pamphlet form.*

A feature of the investigation is the detailed exploration of the electromagnetic field on and near the surfaces of the rails, the object of which was to put methods of calculating the impedances of circuits involving rails on a satisfactory basis. This part of the work has resulted in suggesting a practical meaning for the term "internal reactance" as applied to rails. This is explained and the term is adopted tentatively and used in setting forth results, which, however, are given also in form suitable for use in methods of calculation which involve "total" reactance.

Measured total reactances of the rail checked within 1 per cent the sum of the observed "internal" reactance and the calculated "external" reactance. In calculating external reactances results show that for traffic rails of usual design it should be satisfactory to assume the rail to be equivalent to a cylindrical conductor, the circumference of which is equal to the rail periphery.

Brief discussions are given of the methods and results of the investigations of bond impedance and of temperature effects. Data respecting the chemical, electrical, and magnetic properties of the rails are given, the degree of similarity among the different rail samples is discussed, and single curves for the resistance and the internal reactance of the "best representative rail" are shown.

Internal Reactance

Some explanation perhaps is needed with respect to "internal" reactance as the term is used in this paper. The usual engineering calculation of the reactance of a circuit involving parallel straight conductors proceeds from the assumption that the magnetic field due to the current in a single wire is strictly circular and coaxial with the wire, even in the close neighborhood of the wire. Usually the total reactances "to infinity" appear as the self-reactances in the computation, there being no point in distinguishing between internal and external reactance under the assumption of exact circular symmetry. Although the idea of internal reactance is clear and self-defining only for round wires where circular symmetry obtains, the practical need for the concept, or

for something equivalent, appears only when the field departs radically from circular symmetry as in the case of a railroad rail carrying current. A common procedure in such situations is to imagine the rail or other irregular conductor replaced with an "equivalent" conductor.[1] This latter is a straight round wire of zero internal reactance and of such a diameter that its external reactance "to infinity" is the same as the total reactance of the actual conductor. The fixing of the radius of the equivalent conductor of course requires a knowledge of the total reactance of the actual conductor, which, in the case of a steel rail, usually is inferred from measurements of its reactance out to a parallel wire sufficiently remote to insure that the field at this wire and at all points beyond is sensibly circular.

This method of handling the problem is convenient and for all ordinary purposes it is sufficiently accurate. By itself, however, it does not assure the reliability of any calculated results for circuits involving conductors closer to the rail than the wire used in the measurements from which the total reactance of the rail is inferred, and of course does not touch the question of the shape of the field in the near vicinity of the rail. There are practical situations in which the latter may be important. An example is the self-impedance of a rail with ground return, where the separation between the surfaces of the conductors forming the 2 sides of the circuit (the rail and the earth) is of the order of the height of the rail itself. To apply the formula given by Carson,[2] which contains a term representing internal impedance, requires that a meaning be assigned to this term in the case of the rail.

Considerations of this nature suggest that generally it would be convenient to conceive the reactance of such conductors as rails to be made up of 2 parts: (1) a part, which may be called *internal*, depending upon the material and geometry of the conductor itself, and varying with such conditions as temperature, saturation, etc., much as does the resistance; (2) a part to be calculated on the circular symmetry assumption, as with round wires, which, in contrast with the other, may be called *external*.

In adopting this point of view in the present paper, the internal reactance has been taken as the reactive component of the longitudinal electric intensity at the point of the rail periphery where it is a maximum. The line of the magnetic field that touches the periphery at this point, and is elsewhere outside of the periphery, is then the boundary separating internal and external reactance. This line is sufficiently nearly circular in shape to allow calculation of the external reactance, with the precision needed for engineering purposes, outward from a circle of specifiable radius that is centered on an axis of current concentration at a specifiable position in the rail (see Figs. 5 and 6). "Internal" as used in this way, of course, does not mean within the substance of the rail, part of the magnetic field concerned being outside the latter. The usage is appropriate, however, in that it signifies close association with the rail itself. It is also a *useful* way of extending the idea of internal reactance in a round wire to the complicated case of the rail, whereas it is difficult to see how the reactance associated with the field in the interior of the rail alone could be of practical value in calculations.

It is not intended to imply that the use of the equivalent conductor or total reactance method should be superseded by one based upon these concepts of internal and external reactance; on the contrary, the results of the experiments are given (in Fig. 14) in a form suitable to the former.

[1] References are at the end of the paper.

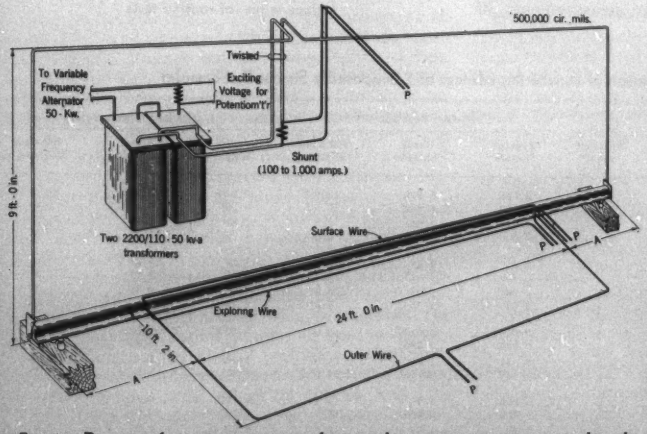


Fig. 1. Diagram of circuit arrangements for impedance measurements on single rails

P, leads (all in twisted pair) to measuring terminals of potentiometer. Dimension "A": for 60-lb rail, 3 ft; for 85- and 100-lb rails, 4 ft 6 in.; for 130-lb rail, 5 ft

Experimental Methods

The circuit arrangement used for most of the work is shown diagrammatically in Fig. 1, as set up for measurements on single rail samples. Where a bond was under investigation the same circuit dimensions were maintained by wrapping the bare cable once around the rail and brazing at the top and the upper surface of the base on each side. All conductors provided for measurement of rail voltage were connected to the rail by soldering to 2 small brass potential taps which were soldered to the web of the rail halfway between the base and top. Tests showed that the distance between adjacent current and potential terminals was ample for the elimination of end effects.

The voltage measuring conductors may be divided into 3 groups, the first consisting of No. 18 B.&S. gauge wires with enamel and single cotton insulation, stretched parallel to the rail axis along the rail surface and touching it, but insulated from it except at the ends. These are called "surface wires" in the following, and the resistances, reactances, etc., measured with them are called "surface resistances," etc. There were 7 positions for these wires in the routine testing, as shown by small letters in Fig. 2. The second group, called "exploring wires," were similar to the surface wires, except that they were held in close proximity to the rail surface instead of against it. They were used only in measurements on the 60- and 130-lb rails, in positions shown in Figs. 5 and 6. The third group was represented by a single No. 12 B.&S. gauge wire (hereafter called the "outer wire") parallel to the rail at a distance of about 10 ft, the ends being connected to the potential lugs by means of wires at right angles; the whole circuit formed, with the rail, a rectangular loop in a plane perpendicular to that of the test current loop.

In an earlier set-up used in measurements on the 90-lb rail and some of those on the 130-lb rail, the planes of the current supply and outer voltage loops made an angle of approximately 108°. In this arrangement, three lengths of 90-lb rail were used, welded together by the thermite process. The same sample of 130-lb rail was tested with both this and the final arrangement of the test circuits, and agreement within 2 per cent was obtained.

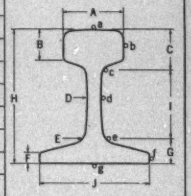
Measurements of rail current and voltages were made with an a-c potentiometer developed according to the design of E. C. Wente.[3] The potentiometer is of the null type, with a precision of at least $\frac{1}{2}$ per cent in magnitude and 0.2 degree in angle. A low frequency amplifier and a low pass filter were used in the detector circuit, and values of resistance, reactance, and impedance given throughout this paper are those corresponding to the fundamental frequencies. Close checks were obtained on measurements of magnitude by the potentiometer and by a vacuum tube voltmeter.

Temperatures were measured with 2 thermometers at the $\frac{1}{3}$ points of the rail sample, with bulbs laid against the bottom of the web (*e* position, Fig. 2) and covered with putty. The average of the 2 thermometer readings was taken as the temperature of the sample. Frequency was measured with a frequency meter of the vibrating reed type.

Rail Samples

Rails used in the tests were loaned by the Virginia Electric and Power Company, the Chesapeake and Ohio Railway, and the Richmond, Fredericksburg, and Potomac Railway, whose courtesy is gratefully acknowledged. There was only 1 sample of the 85-lb rail and 1 of the 100-lb rail, 2 each in the 60- and 130-lb sizes and 3 samples of the 90-lb rail. All samples were new, except the 2 60-lb rails. These had been

	60 lb. Rail	85 lb. Rail	90 lb. Rail	100 lb. Rail	130 lb. Rail
A	2 5/16	2 1/2	2 1/2	2 13/16	3
B	7/8	1 1/8	1 7/16	1 1/4	1 9/16
C	1 1/8	1 3/8	1 9/16	1 9/16	1 7/8
D	1/2	1/2	5/8	11/16	3/4
E	5/8	5/8	3/4	1	1
F	3/16	1/4	5/16	3/8	9/16
G	3/4	7/8	1	1 1/16	1 1/4
H	4 3/16	5 1/8	5	6	6 5/8
I	2 5/16	2 3/8	2 7/16	3 1/2	3 1/2
J	4 1/4	5 3/16	4 3/4	5 9/16	5 9/16
Perimeter	18 1/2	22 3/8	21 3/8	24 5/8	25 3/4
See Note	†	†	†	a	a



Note: Small letters in the table show location of measuring wire (see diagram above) for measurements of resistance and internal reactance. Dimensions in inches.

Fig. 2. Dimensions of test rails and locations of surface wires for routine tests

Table I—Comparison of Surface Impedances of 2 Supposedly Similar Rail Samples

Rail Weight, Lb Per Yd	Frequency, Cycles Per Second	Current in Rail, Amperes	Point of Measurement*	Surface Reactance** Regular Sample	Surface Reactance** Check Sample	Surface Reactance** Per Cent Difference	Surface Resistance** Regular Sample	Surface Resistance** Check Sample	Surface Resistance** Per Cent Difference
60	25	75	f	0.775	0.875	12.9	0.830	0.920	10.9
			e	0.550	0.645	17.3	0.800	0.875	9.4
		700	f	1.21	1.25	2.8	1.81	1.87	3.3
			e	1.00	1.04	4.0	1.78	1.85	3.9
60	60	75	f	1.34	1.48	10.4	1.27	1.41	11.0
			e	0.890	1.01	13.5	1.18	1.32	11.9
		700	f	1.96	2.05	4.6	2.82	2.88	2.1
			e	1.50	1.55	3.3	2.78	2.84	2.2
130	25	75	a	0.565	0.610	8.0	0.500	0.530	6.0
			e	0.340	0.395	16.2	0.451	0.490	8.7
		700	a	0.911	1.01	11.0	1.26	1.32	4.8
			e	0.668	0.765	14.5	1.23	1.28	4.1
130	60	75	a	0.990	1.10	11.1	0.790	0.860	8.9
			e	0.530	0.600	13.2	0.700	0.750	7.2
		700	a	1.52	1.74	14.5	1.99	2.01	1.0
			e	0.990	1.20	20.2	1.90	1.94	2.1

* See Fig. 2. ** In milliohms at 70 deg F for 24 ft of rail.

Table II—Chemical Analyses of Rails

Element	Average Content, Per Cent: First Group	Second Group
Mn	0.97	0.80
S	0.090	0.034
Si	0.007	0.18
P	0.072	0.024
Cu		0.005
Ni		0.01
C	0.50	0.56

Table III—Magnetic Characteristics of Rails

Rail Weight, Lb Per Yd	Permeability, c.g.s. Units: Initial: Magnitude	Initial: Range (%)	Maximum: Magnitude	Maximum: Range (%)	Induction for Maximum Permeability, Gausses
60	90	6	535	9	7,000
85	95	23	615	30	7,300
90	90	5	509	16	6,600
100	85	0 ±	386	9	6,300
130	70	0 ±	356	5	6,000

in service, but, while somewhat rusty, they showed only slight evidence of wear.

The 3 90-lb samples were welded end-to-end as already mentioned, and the length of rail between potential terminals included all of the middle and most of the end rails. The results thus represent averages for the 3 rails. To determine the character of the welds, one of them was sawed through when the assembly was taken apart. The weld appeared to be practically perfect; hence, there was no reason for suspecting that the welded joints might have caused irregularities.

Most of the measurements on the 60- and 130-lb rails were made on one sample; check measurements were made on the other at a low and a high current, and at 25 and 60 cycles. Comparisons are shown in Table I. To a large extent, differences such as those shown should average out in a long stretch of rail. In contrast with these variations, a single sample was found to be remarkably uniform. Thus with the 130-lb rail at 25 cycles, the surface impedance of the middle 12 ft differed in magnitude from half of the result for the full 24 ft by not more than 1.5 per cent for any of the 7 regular surface wire positions (Fig. 2) and the difference in the angle did not exceed 1° in any case. This was with rail currents of 200 and also 400 amp. Equally consistent results were noted at 60 cycles.

If all rail samples may be considered similar, the resistance and internal reactance each multiplied by the rail perimeter should be approximately the same, respectively, for all samples, at fixed frequency and fixed current per inch of periphery. Computation of these 2 products showed that, on the whole, the deviations of their values for the 85- and 100-lb rails from averages taken over all samples were about the same as for other rail sizes for which more than one sample was available; that is, the evidence from this study is that the 85- and 100-lb samples were of as representative a character as the others,

Table IV—Specific Resistance of Rails

Weight of Rail, Lb Per Yd	Specific Resistance at 70 Deg F, μohms-Cm³/Cm	Temperature Coefficient Per Deg F (70 to 160 Deg F)
60	19.8	+0.144
85	18.9	0.159
90	21.4	0.131
100	21.7	0.152
130	22.0	0.146
Means	20.8	+0.146

and results from the former are given without attempt at correction because of their possible non-representative character.

Chemical, Magnetic, and Electric Properties of the Rails

Chemical analyses of the material in the rails classify them into 2 groups, characterized primarily by silicon content and to a smaller extent by content of sulphur and phosphorus. The first group (low silicon) comprises the 60-, 85-, and 90-lb rails; the second group, the 100- and 130-lb rails. The principal features of the chemical analyses (average of 3 rails for the first group and of 2 rails for the second) were as shown in Table II.

For the magnetic tests, samples were machined from the head, the web, and the base of a rail of each size tested. The more significant results are given in Table III.

Figures for both permeabilities are for the particular machined sample giving the largest value. Figures for range represent extreme variations among different machined samples.

Measurements of the specific resistance and its temperature coefficient gave the results shown in Table IV.

Temperature coefficients are expressed as percentages of the resistance at 70 deg F. The coefficient was found to be constant over the range indicated within the precision of the measurements.

The laboratory determinations of chemical, electrical, and magnetic properties were made by the Bell Telephone Laboratories, Inc.

Bonds

Two kinds of bonds were tested. The first, called the "short" bond, consisted of stranded twin conductor equivalent in conductance to No. 4/0 B.&S. gauge copper and about 7 in. long. In practice and as in these tests, the ends of the bond were brazed to the heads of the rails on either side of the joint, a single bond being used. The second bond, called the "long" bond, was of the expanded terminal type, and consisted of a single stranded conductor 33-in. long with conductance equivalent to No. 3/0 B.&S. gauge copper; this bond had sleeves at each end for insertion into $^{3}/_{4}$-in. holes in the web of the rail, expansion against the inside of the hole being accomplished by a steel pin driven into the sleeve. Two bonds of this type, one on each side of the rail, were

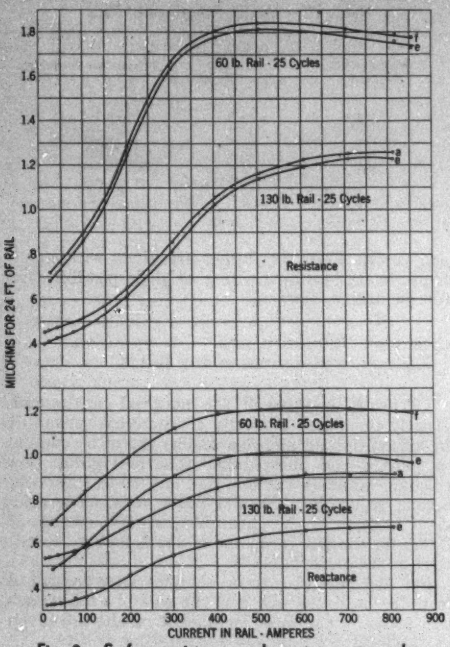

60 lb. Rail - 25 Cycles
130 lb. Rail - 25 Cycles
Resistance
60 lb. Rail - 25 Cycles
130 lb. Rail - 25 Cycles
Reactance
MILOHMS FOR 24 FT. OF RAIL
CURRENT IN RAIL - AMPERES

Fig. 3. Surface resistance and reactance at regular positions of surface wires where they were maximum and minimum, temperature, 70 deg F

Small letters indicate locations of surface wires (See Fig. 2)

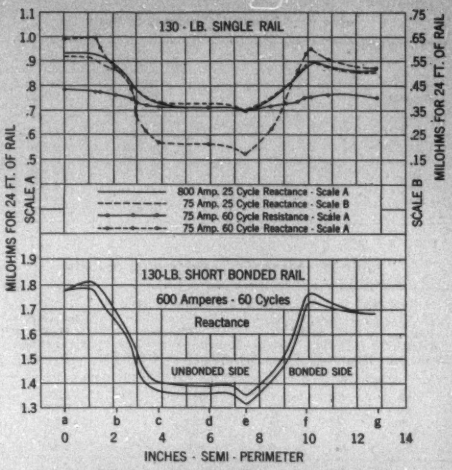

130 - LB. SINGLE RAIL
800 Amp. 25 Cycle Reactance - Scale A
75 Amp. 25 Cycle Reactance - Scale B
75 Amp. 60 Cycle Resistance - Scale A
75 Amp. 60 Cycle Reactance - Scale A
130-LB. SHORT BONDED RAIL
600 Amperes - 60 Cycles
Reactance
UNBONDED SIDE
BONDED SIDE
MILOHMS FOR 24 FT. OF RAIL SCALE A
MILOHMS FOR 24 FT. OF RAIL SCALE B
INCHES - SEMI - PERIMETER

Fig. 4. Variation of surface resistance and reactance around rail periphery at constant rail current, temperature, 70 deg F

Small letters refer to positions shown in Fig. 2

utilized for each joint. Standard fishplates arranged in the usual way (one on each side of the rail) were used for joints with both types of bonds, the long bonds being between the fishplate and the rail.

Tests for the effects of bonds were made only on the 60-lb (short bonds only) and 130-lb rails (both types of bonds). Measurements were made at all 4 frequencies and over the whole range of current.

Results and Discussion

Results in form for practical use are given in Figs. 9 to 15, inclusive, and in Table VII. In the curves, the internal reactance is the surface reactance at that one of the 7 regular measuring positions where it was largest, and the resistance is the surface resistance at the same point. For the 100- and 130-lb rails, this is position *a*, Fig. 2; for the others, it is position *f*. The resistance was found to be practically identical with the resistive component of the voltage drop as measured in the outer wire. Within the precision of the measurements, the 2 components of surface impedance had their maxima at the same peripheral position (see Fig. 4) as would be expected from theoretical considerations.

From a more general point of view, features having sufficient interest to warrant discussion include the field at the surface and in the immediate vicinity of the rail, the degree of concordance of results from the various rail samples, the effects of bonds, and temperature effects.

Field on the Surface and in the Vicinity of the Rail—Internal Reactance

Surface resistance and reactance were measured for all samples at all currents at the maximum and minimum points, *f* (approximately) and *e* for the 60-, 85-, and 90-lb rails, *a* and *e* for the 100- and 130-lb rails. Typical results are shown in Fig. 3. The differences in resistance were small for all rails, running from about 2 per cent at high currents to about 8 per cent at low currents, whereas the surface reactance differed at the 2 extreme points by as much as 2 to 1 for the large rails at low currents. Typical results of more detailed examinations of the field around the periphery, with 11 points of observation in addition to the 7 regular ones, are shown in Fig. 4. The secondary maxima appearing in these curves at or near point *f* become the principal maxima for the 3 smaller rails (for which no curves are shown). In the 85-lb rail surface reactance at 40 cycles and 500 amp, for example, the *f*-maximum exceeds the *a*-maximum by about 2 per cent. The effect of a bond in distorting the field around the periphery is shown in the 2 lowest curves of Fig. 4. In obtaining these curves, the surface wires were placed over the fishplates on both sides in passing the joint. A comparison of results with wire *d* under, and then over, the fishplate showed that considerable flux threaded the fishplate.

In Figs. 5 and 6 are shown the results of measurements of reactance in the vicinity of the rail. The

data are plotted without adjustment other than for temperature and for small accidental variations in rail current. The flattening of the field at the upper corners of the head in the diagrams for 60-lb rails, confirmed by iron-filing figures, possibly is due to a hardening of the rail under service conditions.

As the diagrams show, the maximum surface reactance, which as previously stated is taken as the internal reactance, occurs near the lower corner of the base in the 60-lb rail and (substantially) at the center of the top of the head for the 130-lb rail. The lines of the field through these maximum points (*e.g.*, the 1,100-μ ohm line in the 75-amp diagram of Fig. 6) are the boundaries separating internal and external reactance according to the scheme previously explained.

In each diagram, the broken-line circle is the one to be used in calculations of external reactance, in accordance with the ideas advanced at the beginning of this paper. This circle, of course, is merely a mathematical convenience; and, while its exact location and diameter are of little practical importance, that figures agreeing as well as those of Table V should be obtained for samples so different and for so wide a range of conditions is of interest. The center of each circle is located halfway between the 2 points in which the line of the magnetic field separating internal and external reactance, as described in the preceding paragraph, cuts the vertical line through the rail axis. The radius is taken as the distance from the center to the point at which the line of the field just mentioned touches the rail contour. For example, in the right-hand half of Fig. 5 the center is (approximately) halfway between the lowest and highest points on the 1,250-μ ohm curve, and the radius is the distance from this center to the tip of the base.

Comparisons of reactive voltages observed in the outer wire (Fig. 1) with the sum of the observed internal reactance and the external reactance, the latter calculated as described, show discrepancies of less than 1 per cent. For traffic rails of usual structural design, it should be entirely satisfactory to take the circumference of the external reactance circle equal to the rail periphery.

Representative Rail

Composite curves for resistance and internal reactance, based upon all the rails used in the tests, are shown in Fig. 7. The dotted lines show the maximum errors that would be made in applying the solid curves to find the components of impedance of any tested sample at any of the 4 test frequencies. These deviations amount at the most to about 15 per cent. The curves could not be used, however, with an expectation of this precision, for high-permeability high-conductivity rails such as the exceptional 100-lb rail of Kennelly, Achard, and Dana mentioned later. Using a least square method, the

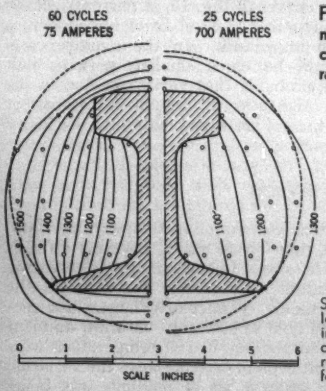


Fig. 5. Magnetic field in vicinity of 60-lb rail at 70 deg F

Small circles show locations of exploring wires. Figures on curves represent reactance in μohms for 24 ft of rail

Table V—Circle for Calculating External Reactance of Rails

Rail Weight, Lb Per Yd	Frequency Cycles Per Second	Rail Current, Amperes	Location of Center of Circle*		Diameter of Circle*	
			h, inches	h/H	d, inches	$\pi d/p$
130	60	75	2.75	0.42	7.75	0.94
	60	700	2.75	0.42	7.75	0.94
	25	75	2.80	0.42	7.60	0.93
	25	700	2.65	0.40	7.95	0.96
60	60	75	2.20	0.52	6.05	1.08
	60	700	2.10	0.50	5.90	1.00
	25	75	2.10	0.50	5.90	1.00
	25	700	2.10	0.50	5.90	1.00

*h = distance of center of circle above bottom of flange.
d = diameter of circle.
H = height of rail.
p = perimeter of rail.

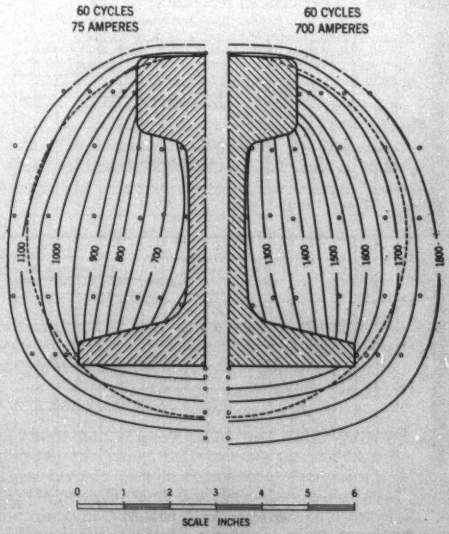


Fig. 6. Magnetic field in vicinity of 130-lb rail at 70 deg F

Small circles show locations of exploring wires. Figures on curves represent reactance in μohms for 24 ft of rail

values of the exponent of the frequency appearing in the ordinates were found to be 0.47 for the resistance and 0.62 for the reactance. The values used in plotting the curves, $^1/_2$ and $^2/_3$, respectively, are more convenient in using the curves and are sufficiently accurate considering the character of the data.

Effects of Bonds

To determine the effects of bonds, the surface impedance of 24 ft of rail, made up of 12 ft each of 2 similar rails having the bond between them, was measured. From the result, an impedance equal to the average impedance of the 2 rails, 24 ft of each, was subtracted; the result was the bond impedance. This method, while obviously capable of improvement for refined investigations, was sufficiently accurate for engineering purposes and saved a good deal of time.

The short-bond tests showed differences in the impedance of the bond as applied to the 2 sizes of rail tested (60- and 130-lb). The impedance on the whole was somewhat larger for the 130-lb rail, but for both components the sign as well as the magnitude of the difference depended upon frequency and current. These differences, while they were frequently substantial fractions of the bond impedance itself, were small parts of the impedance of a rail bonded at usual spacings; thus, for practical purposes, the results could be averaged, as shown in the 8 curves of the upper part of Fig. 15. The maximum error in the use of these curves for either rail with bonds at 33-ft intervals, is estimated at 3 to 4 per cent in resistance, and 1.5 per cent in reactance.

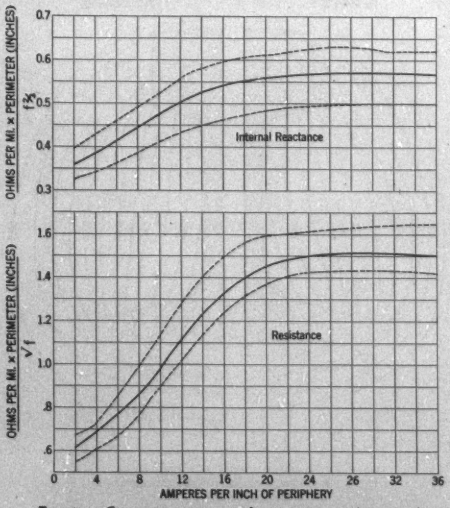


Fig. 7. Composite curves of resistance and internal reactance at 70 deg F for single continuous rail

Curves are based on results from 9 test samples at 4 frequencies. Dashed curves are envelopes of maximum deviations, all samples and frequencies

The short-bond resistance showed well-marked maxima with respect to rail current at all frequencies and the reactance showed similar, though flatter, maxima. The maximum was found to occur uniformly at a smaller current for the 60- than for the 130-lb rail, and, with a single exception, the magnitude of the maximum was increased when the frequency was raised. The resistance and reactance of long bonds were found in every case to exceed corresponding quantities for short bonds, the variation with rail current being like that for short bonds, but with broader maxima.

Since the long-bond data were taken only for the 130-lb rail, it seemed best to express the long-bond impedance in terms of its ratio to the short-bond impedance; this is done in the 2 lower curves of Fig. 15, which apply to all 4 frequencies. It is estimated that the maximum error in the calculated resistance of a length of rail, bonded with long bonds at usual intervals, arising from the use of these lower curves, would not exceed 1.5 per cent. The estimated maximum error in calculating the resistance of a length of long-bonded rail, due to the combined inaccuracies in both sets of curves in Fig. 15, is then about 5 per cent. The precision in internal reactance is possibly not quite so good, owing to inaccuracies involved in taking the lowest curve of Fig. 15 as fully representative. These statements concerning precision apply to extreme cases of deviations of individual measurements from the curves of Fig. 15, at currents chosen to give an unfavorable ratio of bond impedance to continuous rail impedance. In the average case, the errors would be much smaller, perhaps half as large. It is probable that variations due to the condition and tightness of fishplates,[4] imperfect contacts in the case of pin-type bonds, etc., are larger than this in practice.

Temperature Effects

To systematize collection of temperature data, so-called "heat runs" were made, covering all rails except the 90-lb size. In these tests, alternating currents of suitable values were run through the samples to heat them. Particularly in measurements at large currents (700 to 900 amp) with low ambient temperatures, fluctuations in rail temperature were unavoidable; but even in extreme cases the variation in temperature while a set of readings was being made was seldom more than 1.5 deg F. The considerable stretch of time covered by the experiments (conducted during intervals of another investigation) afforded a wide seasonal range of ambient temperatures and made it possible to secure satisfactory checks on the adequacy of the scheme of using ordinary thermometer readings for the rail temperature. The character of these checks may be seen in Fig. 8.

The main results may be stated as follows:

1. The rate, in ohms per degree, at which rail a-c resistance or rail internal reactance increases with rising temperature is substantially constant from 30 to 120 deg F (0 to 50 deg C) and is substantially the same whether the temperature changes affect the entire rail, or are effected by methods that concentrate the generation of heat in a superficial layer.

2. There is no consistent variation in the coefficients with magnitude of rail current, with frequency, or with size of rail.

3. Over-all averages of observations at all frequencies, all currents, and all temperatures are shown in Table VI.

4. The temperature coefficient at the position of minimum electric intensity on the rail periphery is consistently larger than at a position of maximum or large electric intensity, especially for the 130-lb rails.

5. For the 60-lb bonded rail, the temperature coefficients are very nearly the same as for continuous rails. For 130-lb rails, with both short and long bonds, however, the temperature coefficients are both higher (running up toward 0.2 per cent on the average)than for continuous rails.

Comparisons With Other Results

Kennelly, Achard, and Dana[5] made impedance measurements on 10 traffic rail samples of 5 different weights per yard, most of the work being at 25 and 60 cycles. The 100-lb rail used in the present tests ran from 0.5 to 6 per cent lower than the lowest of their 4 similar 100-lb rails in skin-effect resistance-ratio and in total reactance. A fifth 100-lb rail investigated by them, of high permeability and low-resistance, showed differences from the other 4 as large as 80 per cent in resistance. Their results from 2 90-lb rails agree well with those obtained from the authors' 90-lb sample; results from their single 60-lb rail are more divergent from those of this paper. On the whole, one may say that for rails of the same size and of comparable permeability and resistivity characteristics, their results agree with the results given here about as well as the results from different samples of similar rails in either set of experiments taken by itself.

The work of E. R. Benda,[6] published in 1931, did not come to the authors' notice until after the present experiments had been completed. Experimenting on a single rail sample, evidently with ideas similar to those underlying the work with which the present paper is concerned, he found minimum resistive and reactive components both at position *e* of Fig. 2, as in all rails tested by the authors, with the maximum reactive component at *a*, as in the present 100- and 130-lb rails. The maximum resistive component, at position *f* as with the present 60-, 85-, and 90-lb rails, was practically the same as at *a*.

From field explorations like those illustrated in Figs. 5 and 6, Benda located the centroid of total rail current about 0.3 of the distance from bottom of base to top of head, and found that the magnetic field became practically circular at a distance from this centroid equal to about 1.35 times the radius of an "equivalent conductor," defined as the circular conductor of circumference equal to the rail periphery with axis coinciding with the current centroid. (Note that this is not the same as the "equivalent conductor" previously mentioned.) The reactance at the surface of this conductor, calculated from the observed reactance at the point at which the magnetic field becomes circular, was found to be the same as at the top of the head, where it is a maximum. This led Benda to suggest that this reactance be taken as the internal reactance of the rail, and thus that the external reactance be calculated from the surface of the "equivalent conductor" outward. The practical consequences of the differences between this suggestion and the scheme proposed in this paper are insignificant.

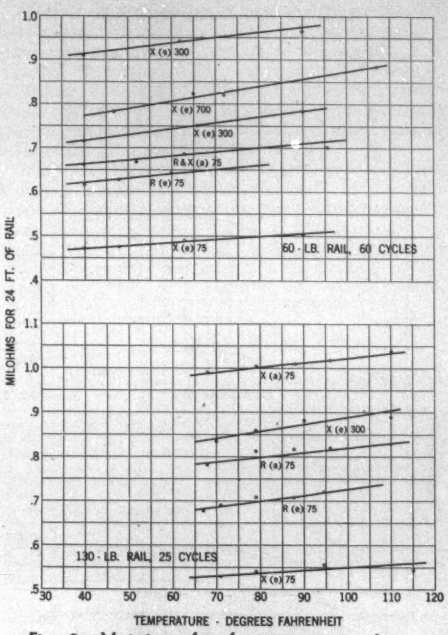


Fig. 8. Variation of surface reactance and resistance with temperature

Dots represent observations made after the rail had been left for long periods without artificial heating. Circles represent observations made after heating with alternating current. Small letters in parentheses signify point of measurement on rail periphery (see Fig. 2). Figures represent rail current in amperes

Table VI—Temperature Coefficients as Percentages Per Deg F, of Resistance and Internal Reactance at 70 Deg F

	60-Lb Rail	85-Lb Rail	100-Lb Rail	130-Lb Rail	Mean, All Rails
Resistance	0.139	0.156	0.210	0.147	0.153
Internal Reactance	0.117	0.150	0.153	0.130	0.132
Mean, resistance, and reactance					0.142

Data for Practical Use

These data (Figs. 9 to 15, and Table VII) are applicable, of course, only to rails generally similar to those tested; and in considering this point, Tables II, III, and IV, and Fig. 2 may be consulted. The d-c resistances of the rails are shown in Table VII.

Curves for the 90-lb rail are in effect means of results from 3 samples, as already explained; those for the 60- and 130-lb rails represent means from 2 samples of each of these sizes. Curves for the 85- and 100-lb rails are from single samples, believed to

Table VII—D-C Resistances of Rails

Rail Weight, Lb Per Yd	Resistance at 70 Deg F, Ohms Per Mile
60	0.0869
85	0.0556
90	0.0587
100	0.0524
130	0.0420

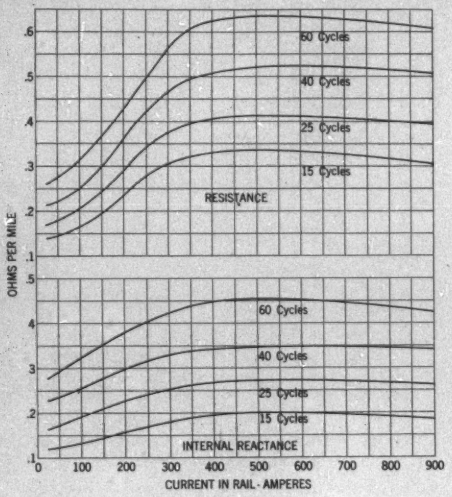


Fig. 9. 60-lb rail

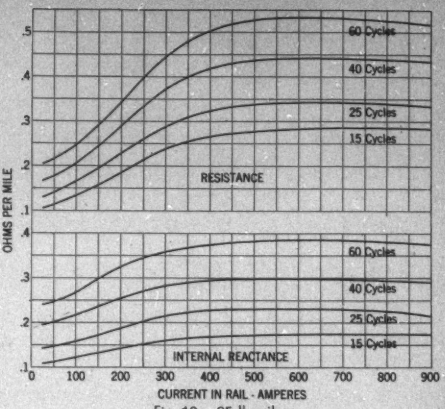


Fig. 10. 85-lb rail

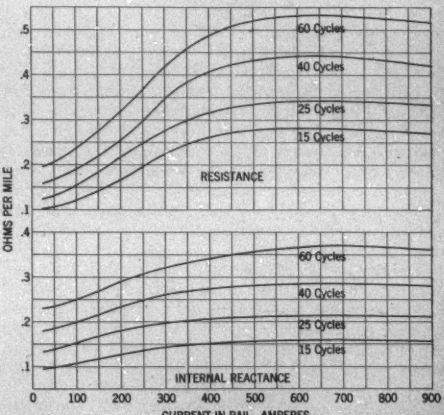


Fig. 11 (above). 90-lb rail

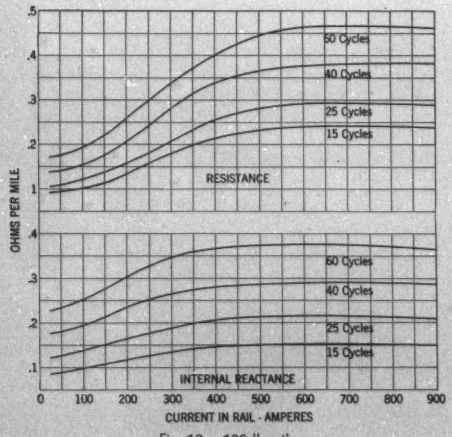


Fig. 12. 100-lb rail

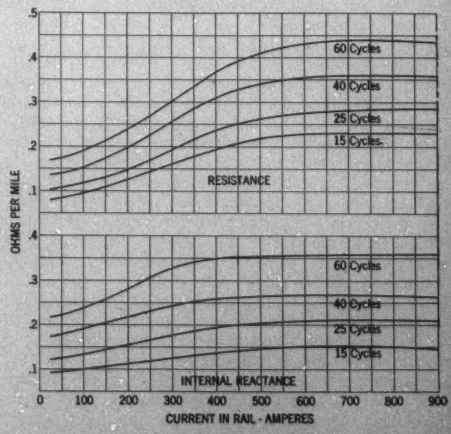


Fig. 13 (below). 130-lb rail

Figs. 9 to 13. Resistance and internal reactance of single continuous rails at 70 deg F

be of a fairly representative character. Curves of Fig. 14 give the total reactance for the test rails, that is, the sum of the internal and external reactances, the latter with infinite flux-radius. In using these curves, it should be noted that temperature corrections should be based on the internal, not the total, reactance.

Correction for bond impedance is the same for all weights of rail; it is about 16 or 18 per cent at the largest, but is considerably smaller for most of the current range. It is given directly for short (U-type) bonds in the 8 upper curves of Fig. 15, and, by applying to these data the factors indicated in the 2 lowest curves, for pin-type bonds (33 in. long in these tests). The corrections, given for bonds at 33-ft intervals, are, of course, inversely proportional to the interval.

Temperature corrections, which usually are not likely to amount to more than 7 or 8 per cent, may be made, after applying the correction for bond impedance, at the rate of +0.14 per cent per deg F excess of temperature above 70 deg F (+0.25 per cent per deg C above 21 deg C) for either resistance or internal reactance.

In calculating external reactance, the rail-current axis may be taken at a point 0.45 of the rail height above the bottom of the base, and the diameter of the circle to be used in such calculations may be taken as rail periphery divided by π.

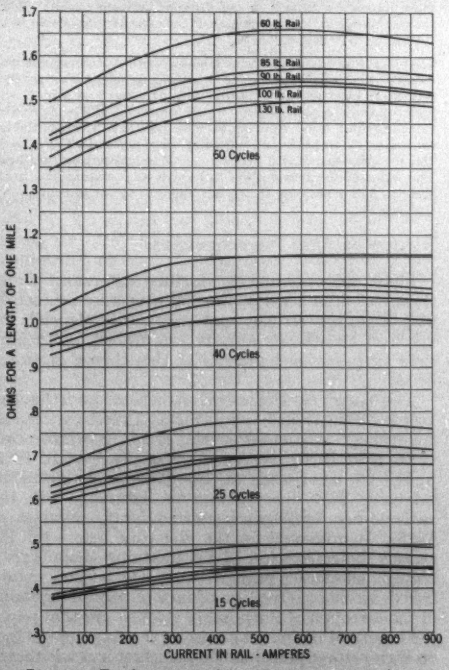


Fig. 14. Total reactance (return current at infinity) at 70 deg F of a one-mile length of single continuous rail, for each of 5 different weights of rail

The curves of Fig. 7 may be useful where the rail is of a size different from, but is otherwise generally similar to, those tested, or where the frequency is different from one of the test frequencies (though, of course, not widely different). This figure also should be of some value in judging what precision may be expected in using data from these rails in estimates concerning other similar rails.

Mr. C. P. Bartgis, Mr. H. Ferris, and Mr. J. H. Harding assisted in the greater part of the field tests. Development work on the a-c potentiometer was done largely by Mr. H. R. Moore. Among those whose advice and assistance contributed materially in the experiments or in working up the results were Mr. A. E. Bowen, Mr. K. E. Gould, Mr. W. L. Gaines, and Mr. K. L. Maurer.

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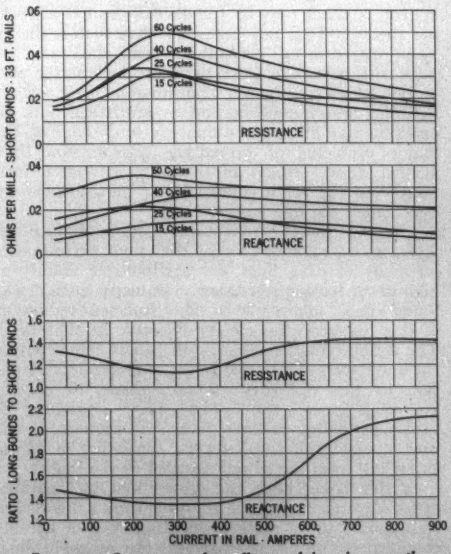

Fig. 15. Corrections for effects of bonds on rail impedance

The 2 groups of 4 curves each give, for short bonds, corrections to be added to the resistance and the reactance per mile of a single continuous rail, bonds being assumed at 33-ft intervals. The 2 lower curves give the factors by which the corrections for short bonds should be multiplied, to obtain corrections for long bonds

Counterpoises for Transmission Lines

Counterpoises are recommended for protecting electric power transmission lines against damage from lightning surges where other methods do not reduce the tower footing surge impedance to the desired level. In this paper a physical explanation of the theory of counterpoises is given together with an analytical solution of parallel counterpoise problems. Of the 2 types studied, the parallel counterpoise is shown to be the more effective.

By
CHARLES L. G. FORTESCUE
FELLOW A.I.E.E.

Westinghouse Elec. and Mfg. Co.
E. Pittsburgh, Pa.

CONSTANT PROGRESS in an art can be made only by the development of a working theory. It is not necessary that such a theory be presented in full perfection. This statement applies with particular force to an art such as the protection of electric power transmission lines against lightning where confirmation by statistical data on experimental lines takes many years. One of the major problems of protecting transmission lines against direct strokes of lightning is related intimately to the earth conditions of the right-of-way over which the line passes.

After the direct stroke theory was announced in 1929, many engineers found that poor performance on many existing lines was attributable mainly to high tower footing resistance. In many cases it was found almost impossible to effect sufficient reduction of this resistance by means available at that time. The counterpoise, consisting of cables connected to the line towers and buried in the ground offers a solution to this difficulty. Counterpoises in general are of 2 types: the "crow's foot" consisting of cables extending radially from the corners of the towers; and the parallel type consisting of cables extending from the towers parallel to the line.

In this paper both the crow's foot and parallel types of counterpoises are analyzed from a theoretical standpoint, and a mathematical analysis of parallel counterpoise problems is given. An example illustrating the method of calculating the protection level of a line equipped with a parallel counterpoise also is given. From the studies upon which this paper is based the following general conclusions may be drawn:

1. Where the earth resistivity is low, no special measures may be required to obtain tower footing surge impedances of 10 ohms or less; the tower foundation structures provide the necessary surface "leakance."

2. Where the earth has fairly low resistance, the normal tower surge impedance may be reduced economically by the use of driven grounds.

3. Where the resistivity of the earth is high, driven grounds have been found to be inadequate and sometimes impractical. For such cases the remedy now is indicated to be the use of counterpoises.

4. Counterpoises have been analyzed and classified as follows: (a) those consisting of wires at right angles to the direction of the line which have the effect only of lowering the surge impedance of the tower footings; (b) those consisting of wires parallel to the direction of the line which have the effect of not only reducing the surge impedance of the tower footings, but also reducing by mutual coupling the difference of potential between line conductors and the tower top. The parallel counterpoise is, therefore, the most effective type, and methods of calculation are presented for the first time that allow analysis of this type of problem.

5. Where a cross-wire counterpoise is used in combination with a parallel counterpoise, its surge impedance should be considered independently of the parallel counterpoise and in parallel with the normal tower footing surge impedance; their resultant surge impedance then should be used in the calculations in place of the normal tower footing surge impedance.

6. To obtain the optimum effect with a given length of wire, where the earth resistivity is not very high, but too high to be taken care of by driven grounds, it may be advantageous to extend the counterpoise for only a portion of the distance between towers. Where the resistivity is very high, however, the counterpoise should be extended for the whole distance.

7. For a projected line tests may be required to predetermine what method of auxiliary grounding will be necessary. For practical estimating purposes, where a line is to be erected on ground with high resistivity a parallel counterpoise consisting of 2 or more wires extending from tower to tower may be considered to make the line equivalent to one having tower footing surge impedances of 10 ohms, and the clearances and insulation can be calculated on that basis. This value of 10 ohms has yet to receive confirmation, but to the author's best knowledge it is a fair value to use at present in projecting a line.

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Nov. 13, 1933. *Not published in pamphlet form.*

Review of Past Developments

Since this paper is a further extension of the theory of protection of transmission lines against direct lightning strokes and necessarily depends on much of the theory already established, a brief review of past developments of this theory seems in order.

The paper by Fortescue, Atherton, and Cox entitled "Theoretical and Field Investigations of Lightning," presented at the A.I.E.E. winter convention in 1929 (see A.I.E.E. TRANS., v. 48, 1929, p. 449–68) was among the first papers relating to the intensive field investigation of lightning with the cathode-ray oscillograph started in the summer of 1928. It presented for the first time before the Institute the conception of the lightning channel as a highly conducting path, after it had become established, having a surge impedance of decreasing value in the direction of the point of stroke. In that paper the theory of the direct stroke as the cause of outages on high voltage transmission lines first was advanced, which theory now has become generally accepted. Based on the ideas presented in that paper, by the

end of 1929 4 principles of protection were established:

1. Proper configuration of ground wires to shield the line conductors against direct strokes.

2. The importance of maintaining low values of tower footing resistance or surge impedance at every tower.

3. Adequate insulation coördinated with the clearance between line and tower taking into account wind deflection

4. Sufficient distance in the middle of the span between line conductors and ground wires to prevent side flash to the conductors when a stroke occurs at the middle of the span.

Although these principles were established as the result of laboratory work in 1929, nothing definite was known regarding the probable magnitude of the direct lightning stroke when it strikes a line. The lightning investigations were continued for the purpose of obtaining as much information as possible on this point. In 1931 2 of the highest surges ever recorded on a transmission line were obtained at Ogemaw on the Arkansas Power and Light Company system. One of these showed a maximum value of 5,000 kv after traveling about $4^1/_2$ miles. It is estimated that had the wood poles not broken down on the front of the wave, the lightning stroke probably would have reached a value of 20,000 kv. As a result of the laboratory work done in 1930 and the previous years, 20,000 kv was decided on as the probable magnitude of severe lightning strokes with the reservation that exceptionally severe strokes might reach even higher values, but were so exceedingly rare that it would not be practical to design lines to withstand these values.

The portable lightning generator used at Stillwater, N. J., contributed a great deal to this progress in showing the importance of the surge impedance of the tower and the reflections set up in the tower after a lightning stroke. The effect of this surge impedance was expressed in the form of curves and added to the theory; it was presented in a discussion by J. J. Torok, of the 1931 lightning papers presented at the A.I.E.E. North Eastern District meeting, Rochester, N. Y., May 6–9, 1931. The effect of corona in increasing the coupling between ground wires and line wires at midspan and in reducing the clearance necessary to prevent side flash due to a direct stroke at midspan was added in 1932. The complete theory taking into account the surge impedance of the towers, the consequent reflections in the tower structure, and the effect of corona on the coupling factors was given in a paper presented by the author before the International Electrical Congress at Paris in June, 1932, entitled "La Foudre et ses Effets sur les Lignes Aeriennes."

Counterpoise Tests at Stillwater

The preceding introduction outlines the progress of the art of protection of transmission lines against direct lightning strokes up to the present time, and points out the various influences that contributed to this development. It may be seen that the present theory presumes the ability to obtain low tower footing resistance at all points of the line right-of-way. As soon as the direct stroke theory was announced in 1929 many utility engineers found that poor performance on many existing lines was due mainly to high tower footing resistance, and set about to remedy this condition. In many cases, it was found almost impossible to effect sufficient reduction by the means available at that time. It was decided, therefore, to include in the test schedule at Stillwater in the summer of 1929 an investigation on artificial means for obtaining satisfactory grounds for tower footings. This work was done on the 220-kv Roseland-Bushkill line of the Public Service Electric and Gas Company of New Jersey, which was being installed at that time and of which a length of 9 miles with ground wires omitted was made available for these tests. An account of this investigation is given in the paper by Conwell and Fortescue entitled "Lightning Laboratory at Stillwater, New Jersey," presented at the A.I.E.E. winter convention of 1930 (see A.I.E.E. Trans., v. 49, 1930, p. 872–6) and the discussion by A. S. Brookes in which further data was added. Although it was impossible to carry the work to completion, some interesting results, contained in Table I of that paper, were obtained. Based upon a surge impedance of 450 ohms for the line and a corona radius of $^1/_6$ ft, which corresponds to a potential of 500 kv, the depth of the ground plane appears to be about 50 ft below the surface of the earth. The buried cable, which was connected to the footings of towers 39, 40, and 41, reduced the tower footing surge impedance from 83 to 44.2 ohms at tower 39; from 128 to 26.4 ohms at tower 40; and with tower 41 alone connected to the buried cable its tower footing impedance was reduced from 46 to 18.8 ohms. The reduction in surge impedance of tower 39 indicates that the buried cable had a surge impedance of 95 ohms; for tower 40, it was 33 ohms; and for tower 41, 32 ohms. It may be observed that they are fairly consistent. The surge impedance in parallel with tower 41 is somewhat less than half that in parallel with tower 39, although practically the same as that at tower 40. It may be supposed that the surge impedance at tower 40 is affected by reflections from tower 41 and that the low surge impedance of tower 41 is due to a higher leakage factor at that portion of the right-of-way.

Obviously, the data is too meager to do much with in the way of generalization; but if a factor K be taken to represent the effect of the capacitance and "leakance" of the buried cable, its value appears to be between 8 and 16, which would not be excessive for a wire in earth of fairly low resistivity. The equivalent surge impedance obtained in this manner has, of course, no real existence as a constant, but changes in value with time and the duration of the applied potential. This explains why the d-c measurement frequently gives values that are too low. For instance, if a constant electromotive force be applied to an infinite cable in a homogeneous medium of low resistivity, the current will build up exponentially and in time will approach a constant value; the $r = E/I$ thus obtained is the equivalent of the footing resistance as measured by d-c means. The surge impedance as measured by a surge generator with a steep wave is an average transient value and is ap-

plicable with a fair degree of approximation to the relative short surges produced by lightning.

General Discussion of Counterpoises

For purposes of discussion a "crow's foot" will be considered as a counterpoise in which 4 wires extend radially from the tower footing at an angle of 45° with the direction of the line. The "parallel counterpoise" shall be considered as one or more wires extending in each direction from the tower footing parallel to the transmission line. The parallel counterpoise does not necessarily extend from tower to tower; as a matter of fact, in some cases it should not do so. The first thing to find out in discussing these 2 types of counterpoises is whether there is any appreciable reduction of the surge impedance in multiple with the normal tower footing surge impedance, by using the crow's foot arrangement, using 2 wires in each case. In the crow's foot arrangement, since the wires are at right angles to each other, there will be no mutual surge impedance between the 2. Considering 2 of the radial conductors of the crow's foot, if the effective radius of one conductor from the standpoint of corona is 0.166 ft and the depth of the earth plane is 50 ft, the surge impedance of the 2 in multiple will be

$$\frac{1}{2} \cdot \frac{60}{\sqrt{K}} \log_e \frac{100}{0.166} = \frac{192}{\sqrt{K}}$$

Consider 2 parallel conductors of the parallel counterpoise having the same effective radius 40 ft apart, the geometric mean radius of the 2 will be $\sqrt{0.166 \times 40} = 2.58$, and the joint surge impedance will be

$$\frac{60}{\sqrt{K}} \log_e \frac{104}{2.58} = \frac{222}{\sqrt{K}}$$

Considering the same arrangements but assuming 200 ft for the equivalent depth of the earth plane for high resistivity earth, the equivalent surge impedance may be computed in a similar manner for the crow's foot counterpoise as

$$\frac{1}{2} \frac{60}{\sqrt{K}} \log_e \frac{400}{0.166} = \frac{234}{\sqrt{K}}$$

and for the parallel counterpoise as

$$\frac{60}{\sqrt{K}} \log_e \frac{400}{2.58} = \frac{302}{\sqrt{K}}$$

From the foregoing calculations it may be assumed, therefore, as far as the surge impedance that operates in parallel with the normal tower footing surge impedance is concerned, that for the same amount of wire there is a slight advantage in favor of the crow's foot counterpoise. If 8 radial wires be used in the crow's foot arrangement, the surge impedance is approximately equal to $^1/_4$ that of the foregoing parallel counterpoise. From this fact may be formed some idea of the reduction in tower footing surge impedance that may be effected by going as far as is practicable with the crow's foot arrangement. If the resistivity of the soil is very high, K may be assumed equal to 4. This will give 37.5 ohms approximately, using the higher value of earth resistivity. Since in such a case the normal tower footing surge impedance is likely to be not less than 200 ohms and may approach 1,000, it may be seen that such a counterpoise would reduce the effective tower footing surge impedance to 31.6 ohms for a normal 200-ohm footing; this is too high a value to give adequate protection, the requirement being 10 ohms or less for a well insulated line. In moderately low resistivity soil K may be assumed equal to 9. Using the first example, 18.25 ohms is obtained as the surge impedance, which may be effective provided the normal tower footing is fairly low; however, under these conditions driven grounds probably would be still more effective and more economical.

The values of K used in the preceding paragraph for low resistivity soils are estimated. There is little or no data available, as far as the author is aware, on the surge impedance of counterpoises. Some data recently has been presented on counterpoises which indicate rather high soil resistivity. Where the resistivity of the soil is very high, the surge impedance of a counterpoise may be less than the resistance obtained by d-c measurements, so that d-c measurements in general are not a measure of the effectiveness of a counterpoise system. Data obtained at Stillwater is too meager and was obtained with a small surge generator. It is believed that a large capacity generator of at least 2,000,000 volts should be used so as to obtain the effects of corona in the soil, which it is believed would reduce the surge impedance materially. Whatever effectiveness has been obtained with crow's foot grounds, is believed to have been due very largely to the parallel counterpoise effect. There is no sharp line of demarcation between the 2 types of counterpoises, both to some extent having the same features in common.

In his discussion of the 1930 paper by Conwell and Fortescue, A. S. Brookes gives a curve showing the reduction of surge impedance of a given tower for different lengths of connected cable; which is reproduced in Fig. 1. To interpret this curve it must be remembered that as the cable length is increased in soil of fairly low resistivity the attenuation of the current due to leakage becomes greater and greater. The potential measured at the tower is the resultant

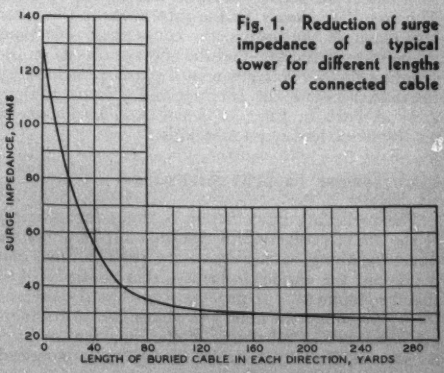

Fig. 1. Reduction of surge impedance of a typical tower for different lengths of connected cable

of all the reflections that take place in the buried cable and of the effects of the attenuation. If the curve of surge impedances given is assumed to be asymtotic to the effective surge impedance of the tower footing with a very long counterpoise, this would indicate a surge impedance of approximately 32 ohms for a buried cable extending in both directions from a tower footing, which value seems very low.

Practical Experience With Lines Indicating Counterpoise Effects

Some 66-kv lines with overhead ground wires built along the right-of-way of railroads have shown exceptionally good performance. With the usual insulation and clearance for such lines, their performance cannot be accounted for by the low tower footing surge impedance alone and must, therefore, be credited to the counterpoise effect due to paralleling rails. A notable example illustrating this correspondence is a $12^1/_2$-mile 69-kv line paralleling a railroad, which has a record of one outage in 15 years though exposed to lightning storms of the usual severity experienced in that region.

During the first 3 lightning seasons of operation, that is 1926 to 1928, inclusive, of the Wallenpaupack-Siegfried 220-kv line of the Pennsylvania Power & Light Company, a considerable number of lightning flashovers was experienced with a disproportionately high percentage of this total concentrated at High Knob, a terrain prominence and the point of highest elevation of the line about 12 miles from Wallenpaupack. High Knob is a hill of solid rock, with a thin layer of soil where not entirely exposed. Realizing the necessity of augmenting the protection afforded by the overhead ground wires, after weighing such experience as they could gather from operating companies and results from lightning research in the high voltage laboratories and in the field, Mr. Nicholas Stahl, chief engineer of the Pennsylvania Power & Light Company, and Mr. A. E. Silver, consulting electrical engineer of Electric Bond & Share Company, recommended the installation of a buried counterpoise over a distance of $2^1/_2$ miles at High Knob. This counterpoise, consisting of 2 continuous No. 2/0 B.&S. gauge copper wires, was installed in the spring of 1929, being completed during May.

Being encouraged by the initial results from the buried counterpoise at High Knob and desirous of improved performance in the remaining $22^1/_2$ miles of the 25 miles total of overhead ground wire sections of the Wallenpaupack line, the Pennsylvania Power & Light Company, after further discussions between their engineers and those of the Westinghouse company, installed crow's feet at each tower throughout the $22^1/_2$ miles. Over $17^1/_2$ miles of this installation was made early in 1930, and the remaining 5 miles early in 1931. These crow's feet consist of buried cables in 4 directions, each extending 50 ft out from the tower. The portions of the line equipped with these 2 types of artificial grounds probably embrace the worst localized exposure to lightning on the Wallenpaupack line.

Results to date since the completion of these respective installations, from the information that the writer has obtained, are as follows: The $2^1/_2$-mile portion of the line over High Knob equipped with the buried longitudinal counterpoise, has not had one insulator assembly flashed by lightning. The $22^1/_2$ miles of the line equipped with crow's feet have had a substantial reduction of flashed insulators, compared with previous experience. Table I brings out this comparative performance in more detail.

Table I—Flashed Insulator Assemblies on a 25-Mile Section of the Wallenpaupack-Siegfried 220-Kv Line

Year	Parallel	Crow's Foot	Station Protective Gaps
1930	0	2	4
1931	0	1	4
1932	0	2	2
1933	0	0	1

While $2^1/_2$ miles of line statistically is not enough to draw any definite conclusion from, even though it shows a perfect record over 5 lightning seasons, the performance of this portion of the line when compared with the $22^1/_2$-mile portion equipped with crow's foot counterpoises is quite significant; and when considered in the light of experience with other existing lines, which appear to owe their high record to parallel counterpoise effects, the result is quite convincing. Doubtless the performance of the $22^1/_2$-mile portion still could be improved by using more wire in the counterpoises, but from theoretical considerations the possible improvement does not appear to be sufficient to bring it to a par with the portion of the line over High Knob equipped with parallel counterpoise.

Physical Explanation of Theory of Parallel Counterpoise

Theory of counterpoises has been a matter of speculation for the last 3 or 4 years. The surge impedance of the counterpoise in which is included the effect of distributed inductance, capacitance, and leakance has been recognized as playing an important part in its effectiveness. Corona formation undoubtedly also plays a large part by increasing the capacitance and leakage and probably reducing the inductance. It has been shown that in respect of surge admittance a parallel counterpoise with 2 wires 40 ft apart extending parallel from the towers a given distance in both directions is not materially different from a crow's foot counterpoise of 4 wires extending radially the same distance at an angle of 45° with the direction of the line. To explain the theory of the parallel counterpoise effect, the overhead ground wires and the buried counterpoise wires running parallel to the line should be considered as in effect a transmission system of comparatively low surge impedance, the tower being merely the cross connection between the parallel wires of the system. The conductors must be considered as a second parallel system insulated from the first sys-

tem, but mutually coupled with the first system through the mutual surge impedance between ground wires and line wires, and counterpoise wires and line wires.

Obviously any surge currents passing through the ground wires and counterpoise wires will raise the potential of the line conductors (through the mutual surge impedance between these and the line conductors) bringing the potential of the line wires closer to the potential of the system comprising the ground wires and line wires. The difference of potential between the ground wires and the counterpoise wires is determined by the surge impedance of the tower and the reflections therein. When the counterpoise is absent and the tower footing surge impedance is high, the ground wires and tower will be raised to a high potential above true zero when the tower is struck, because the surge impedance of the ground wires and tower footing is not low enough to keep the potential down. The potential of the line wires also will be raised through the mutual surge impedance between overhead ground wires and line wires, but not enough to prevent flashover of the insulator due to the difference of potential between line wires and ground wires.

The addition of the parallel counterpoise wires now will be considered. First of all, the surge impedance of the counterpoise will reduce the potentials of line and ground wire in the same proportion so that the difference of potential between them will be reduced proportionately. This would be the only effect of a counterpoise having the same surge impedance as the parallel counterpoise, but extending radially from the tower at right angles to the line; in effect, it functions by lowering the tower footing surge impedance. In the case of the parallel counterpoise, this lowering of the potential by reduction of tower footing surge impedance is obtained and, in addition, the current in the counterpoise through the mutual surge impedance between counterpoise and line wires will raise the potential of the latter so that it more nearly approaches that of the ground wire and tower top; consequently, the difference of potential between line wire and tower will be reduced greatly, and with adequate insulation will not cause a flashover. These phenomena are illustrated by experiences in the Adirondack Mountain (N. Y.) region where lightning punctured cables buried in soil of high resistivity. It was found that cables having no outer metallic covering were affected, but armored cables were not. One remedy that was effective was to place wires in the same trough about a foot or 2 above the cable. A better remedy was to place a light stranding of wires over the whole cable. The action of the counterpoise and ground wires is similar to that of the metallic stranding over the cable except that in the latter case the coupling is very high so that the difference of potential between the inner conductor and the outer stranding is very small.

Different Types of Counterpoises

It will be clear now to those who have followed the reasoning in this paper that there are 2 distinct types of counterpoise effects: that due to wires radiating from the towers at right angles to the line, and that due to wires radiating from the towers in a direction parallel to the line, the former having the effect of merely increasing the surge admittances of the tower footing by adding its surge admittance to that of the natural surge admittance of the tower. The latter not only increases the surge admittance of the tower footing by practically the same amount as the former for a given length, but also through its mutual surge impedance and the current passing through it, raises the potential of the line conductor to a value approaching more nearly that of the overhead ground wires thereby reducing the stress on the line insulation. This effect must not be considered small; indeed, it is quite large because of the large amount of current in the surge passing into the counterpoise. It seems proper to point out now that in soil of comparatively low resistivity, in order to get a large part of the benefit of a parallel counterpoise, the counterpoise wires need not extend from tower to tower. The weak point of the transmission line from an insulation standpoint is usually the line insulator and, fortunately, at that point the full coupling effect due to the counterpoise is realized. Beyond the tower the insulation strength rapidly increases, so that if the difference of potential increases because of attenuation of the surge current in the counterpoise, this need not cause concern as there is ample insulation strength away from the tower. However, the portion of the counterpoise parallel with the line should be long enough so that what current is reflected will be small and will have attenuated to a negligible amount before it reaches the tower.

Analytical Solution of the Parallel Counterpoise Problem

In the preceding few paragraphs, it has been attempted to explain the mechanism of the parallel counterpoise in simple terms so that those who do not care to take the time to follow out the analytical solution may form a clear idea of what it does. Appendix I presents the analytical solution based upon a homogeneous medium, by the theory of multiple circuits considering the lines as being distortionless. In actual practice the medium is not homogeneous and some correction must be used to obtain the approximate values of surge impedances and mutual surge impedances. For the overhead ground wires and line wires, the usual convention has been used based upon the distance of the wires from their images considering the medium as air. Considering the effect of the surge propagated in the counterpoise, which is buried in the earth, a suitable value of K is used so that its surge impedance is the surge impedance that would be obtained if the sole medium were air, divided by $\sqrt{K}$. In considering its mutual surge impedance to the line conductors and the overhead ground wires, the field due to the surge current flowing therein is conceived to consist of 2 parts, one of which moves with the velocity of light and is porportional to s, where s is less than unity, and has surge impedance and mutual surge impedance pro-

portional to unity; and a second portion moving with velocity $V/\sqrt{K}$ whose magnitude is proportional to $\sqrt{K} - s$, where v is the velocity of light. The current due to the combined natural surge admittance of the footing and that of a cross counterpoise, if any, is included and is taken to be proportional to m. Calling the current concerned in these effects I_1, I_K, and I_g, respectively,

$$I_1 : I_K : I_g :: s : \sqrt{K} - s : m$$

$$\therefore I_1 = \frac{s}{m + \sqrt{K}}(I_1 + I_K + I_g)$$

$$I_K = \frac{\sqrt{K} - s}{m + \sqrt{K}}(I_1 + I_K + I_g)$$

$$I_g = \frac{m}{m + \sqrt{K}}(I_1 + I_K + I_g)$$

Now I_g has no mutual surge impedance, and the mutual surge impedance of I_K is proportional to $1/\sqrt{K}$ while that of I_1 is proportional to 1. Therefore, the mutual surge impedance of the total current $I_1 + I_K + I_g$ is proportional to the factor

$$\frac{s}{m + \sqrt{K}} \times 1 + \frac{\sqrt{K} - s}{m + \sqrt{K}} \times \frac{1}{\sqrt{K}} + \frac{m}{m + \sqrt{K}} \times 0$$

This is equal to

$$\frac{(s + 1)\sqrt{K} - s}{m + \sqrt{K}} \cdot \frac{1}{\sqrt{K}}$$

If the surge impedance due to the section of line and counterpoise on one side of the tower be considered, then to determine m, $2Z_G$, where Z_G is the normal tower footing surge impedance, must be used thus

$$2Z_G = \frac{Z_1}{m}$$

so that

$$m = \frac{Z_1}{2Z_G}$$

The value of Z_G is supposed to be known and, unless a cross counterpoise is used, is dependent only on the normal tower footing surge impedance; Z_1 is the surge impedance of the parallel counterpoise considering the medium to be homogeneous and air.

The K used in the preceding discussion should be the true specific inductive capacity of the soil. This will vary over a wide range. The value for pure distilled water is about 70; therefore K would be expected to be high for deep alluvial or marshy soil, possibly 9 or more. For light dry sandy soil, K may be low, but moisture is always present in alkaline earths and salts so that K is not expected to be less than 4. In general, the value of the apparent surge impedance is affected not only by K but also by the leakance. Fortunately, where leakance is high K also is high and one tends to offset the other. However, for short steep waves resistance and leakance affect the surge impedance very little, so that the proper value of K may be obtained by tests made on buried counterpoises using a surge generator giving a steep front wave. Resistance has a tendency to increase the surge impedance while leakance has a tendency to decrease it, so that they offset each other to a certain extent; when they completely balance each other, the circuit is distortionless. In the present problem it is not necessary to consider the attenuation due to leakance and resistance nor the distortion because the values involved are at the threshhold of the ground wire and counterpoise system. It should be noted that the working theory applies not only to the parallel counterpoise, but also to the cross counterpoise and any combination of the 2 types. The surge impedance of the cross counterpoise is to be considered as independent of the parallel counterpoise and in multiple with the normal tower footing surge impedance.

While the author does not attempt to justify on theoretical grounds the approximation given in the previous paragraph, it appears to be consistent and is flexible and easy to use; furthermore, it works in well with the analytical theory and is believed to give conservative results. Possibly further study will develop a more scientific way of arriving at an approximation. In Appendix II is worked out a numerical example by this method using $s = 1$.

Prospective Tests

Since so much depends on the mutual surge impedance between the counterpoise and overhead lines, tests are under way on a line built near the Trafford laboratory of the Westinghouse company for the purpose of measuring some of these values. It is hoped that by the time this paper is presented some data will be available that will be of help in determining the proper constants to use in applying the analytical solution to practical problems.

Appendix I—The Parallel Counterpoise

One of the difficulties of problems of this kind is to provide adequate nomenclature for all the quantities involved. Since there will be a change of value of all surge currents and electromotive forces every half-period, it will be necessary to distinguish between the values of a given current during the intervals. The currents in the ground wires and counterpoises all will be traveling positively; in the tower will be both positively and negatively traveling surges that must be taken into account; while in the lightning channel both kinds exist, but only the positively traveling waves need be taken into account. Currents and electromotive forces will be designated by giving them a subscript S for the lightning channel, A and B for the ground wire and counterpoise, C for the line, and T for the transmission tower. The half-period is designated by the Greek letter Tau (τ) and the values occurring during the rth half-period will be designated by adding the letter r to the subscript, thus $E_{A\tau}$, $E_{T\tau}$, $E_{B\tau}$, $E_{T\tau}$, etc. A positively traveling wave will be designated by placing the sign "$\cdot$" over the symbol, thus $\dot{E}_{T\tau}$, and a negatively traveling wave by placing the sign in reverse as "$\cdot$," example $\dot{E}_{T\tau}$. A positive traveling wave resulting from reflection at the beginning of the rth period would be designated $\dot{I}_{A\tau}$, $\dot{I}_{B\tau}$, etc., similarly negative traveling waves will be designated $\dot{I}_{T\tau}$, $\dot{I}_{B\tau}$, etc.

There are 3 general terminal conditions to be accounted for.

1. Junction of lightning channel, tower, and ground wires.
2. Junction of tower footing and counterpoise.
3. Junction of tower, channel, and ground wire for negatively traveling waves in the tower only.

At the beginning of the first half-period no electromotive force is impressed at the junction of the tower footing and counterpoise so

that for the potential of the transmitted surge on the ground wire and tower in multiple

$\dot{E}_S + \dot{E}_S$ = transmitted potential

$\dot{E}_S = -I_{S1}Z_S$

The transmitted current is

$I_{S1} + I_{S1} = I_{A1} + I_{T1}$

$-I_{S1}Z_S = I_{S1}Z_S - I_{A1}Z_S - I_{T1}Z_S$

$\dot{E}_S + \dot{E}_S = \dot{E}_S - I_{S1}Z_S$

$= \dot{E}_S + I_{S1}Z_S - I_{A1}Z_S - I_{T1}Z_S$

$= 2\dot{E}_S - I_{A1}Z_S - I_{T1}Z_S$

Therefore,

$2\dot{E}_{S1} - I_{A1}Z_S - I_{T1}Z_S = Z_{AA}I_{A1} + Z_{AB}I_{B1}$

or

$$\dot{E}_{S1} = \left(\frac{Z_S}{2} + \frac{Z_{AA}}{2}\right)I_{A1} + \frac{Z_{AB}}{2}I_{B1} + \frac{Z_S}{2}I_{T1}$$

$2\dot{E}_{S1} - I_{A1}Z_S - I_{T1}Z_S = Z_TI_{T1}$

or

$$\dot{E}_{S1} = \frac{Z_S}{2}I_{A1} + \left(\frac{Z_S}{2} + \frac{Z_T}{2}\right)I_{T1}$$

At the junction of the tower and counterpoise there is no impressed surge, and the surge impedance of the tower is Z_T so that the complete set of equations is

$$\dot{E}_S = \left(\frac{Z_S}{2} + \frac{Z_{AA}}{2}\right)I_{A1} + \frac{Z_{AB}}{2}I_{B1} + \frac{Z_S}{2}I_{T1}$$

$$\dot{E}_S = \frac{Z_S}{2}I_{A1} + \left(\frac{Z_S}{2} + \frac{Z_T}{2}\right)I_{T1}$$

$$0 = \frac{Z_{AB}}{2}I_{A1} + \left(\frac{Z_T}{2} + \frac{Z_{BB}}{2}\right)I_{B1}$$

By eliminating I_{T1}, these are reduced to

$$\left.\begin{aligned}\frac{Z_T}{Z_S + Z_T}\dot{E}_S &= \left(\frac{Z_SZ_T}{2(Z_S + Z_T)} + \frac{Z_{AA}}{2}\right)I_{A1} + \frac{Z_{AB}}{2}I_{B1}\\ 0 &= \frac{Z_{AB}}{2}I_{A1} + \left(\frac{Z_T}{2} + \frac{Z_{BB}}{2}\right)I_{B1}\\ I_{T1} &= \frac{2E_S}{Z_S + Z_T} - \frac{Z_S}{Z_S + Z_T}I_{A1}\end{aligned}\right\} \quad (1)$$

At the junction of counterpoise and tower,

$I_{T1} - I_{B1} = 0$

$I_{T1} = I_{B1}$

Therefore,

$$\left.\begin{aligned}\dot{E}_{T1} &= Z_TI_{T1}\\ \dot{E}_{T1} &= -Z_TI_{T1} = -Z_TI_{B1}\end{aligned}\right\} \quad (2)$$

At the beginning of the second half-period there are 2 sets of equations to solve in which portions of I_{A1} designated by I'_{A1} and I''_{A1} and portions of I_{B1} designated by I'_{B1} and I''_{B1} are involved independently. They are

$$\left.\begin{aligned}0 &= \left(\frac{Z_SZ_T}{2(Z_S + Z_T)} + \frac{Z_{AA}}{2}\right)I'_{A1} + \frac{Z_{AB}}{2}I'_{B1}\\ \dot{E}_{T1} &= \frac{Z_{AB}}{2}I'_{A1} + \left(\frac{Z_T}{2} + \frac{Z_{BB}}{2}\right)I'_{B1}\\ \dot{E}_{T1} &= \left(\frac{Z_T}{2} + \frac{Z_{AA}}{2}\right)I''_{A1} + \frac{Z_{AB}}{2}I''_{B1} - \frac{Z_T}{2}I''_{S1}\\ \dot{E}_{T1} &= \frac{Z_T}{2}I''_{A1} - \left(\frac{Z_T}{2} + \frac{Z_S}{2}\right)I''_{S1}\end{aligned}\right\} \quad (3)$$

$$0 = \frac{Z_{AB}}{2}I''_{A1} + \left(\frac{Z_T}{2} + \frac{Z_{BB}}{2}\right)I''_{B1}$$

By eliminating I''_{S1},

$$\left.\begin{aligned}\frac{Z_S}{Z_S + Z_T}\dot{E}_{T1} &= \left(\frac{Z_SZ_T}{2(Z_S + Z_T)} + \frac{Z_{AA}}{2}\right)I''_{A1} + \frac{Z_{AB}}{2}I''_{B1}\\ 0 &= \frac{Z_{AB}}{2}I''_{A1} + \left(\frac{Z_T}{2} + \frac{Z_{BB}}{2}\right)I''_{B1}\end{aligned}\right\} \quad (4)$$

Adding eqs 3 and 4

$$\left.\begin{aligned}\frac{Z_S}{Z_S + Z_T}\dot{E}_{T1} &= \left(\frac{Z_SZ_T}{2(Z_S + Z_T)} + \frac{Z_{AA}}{2}\right)I_{A1} + \frac{Z_{AB}}{2}I_{B1}\\ \dot{E}_{T1} &= \frac{Z_{AB}}{2}I_{A1} + \left(\frac{Z_T}{2} + \frac{Z_{BB}}{2}\right)I_{B1}\end{aligned}\right\} \quad (5)$$

Since there are no induced potentials in the tower structure nor in the channel, at the junction of the tower channel and ground wire transmitted potential is

$\dot{E}_{T1} + \dot{E}_{T1} = (I_{T1} - I_{T1})Z_T$

By the principle of continuity of current at a junction point, the current flowing toward this point $-(I_{T1} + I_{T1})$ must be equal to the current flowing from it $(I_{A1} - I_{S1})$ or

$-I_{S1} = -(I_{A1} + I_{T1} + I_{T1})$

but since there are no induced potentials in the channel, the potential at the junction

$\dot{E}_{T1} + \dot{E}_{T1} = -Z_SI_{S1} = -Z_S(I_{A1} + I_{T1} + I_{T1})$

or

$(I_{T1} - I_{T1})Z_T = -Z_S(I_{A1} + I_{A1}) - Z_SI_{T1}$

Therefore

$I_{T1}(Z_S + Z_T) = -Z_S(I_{A1} + I_{T1}) + Z_TI_{T1}$

or

$$I_{T1} = -\frac{Z_S}{Z_S + Z_T}(I_{A1} + I_{T1}) + \frac{Z_T}{Z_S + Z_T}I_{T1}$$

Therefore

$$\dot{E}_{T1} = -\frac{Z_S + Z_T}{Z_SZ_T}(I_{A1} + I_{T1}) + \frac{Z_T{}^2}{Z_S + Z_T}I_{T1} \quad (6)$$

At the junction of the tower and counterpoise,

$I_{T1} + I_{T1} - I_{B1} = 0$

$I_{T1} = -(I_{T1} - I_{B1})$

$$\dot{E}_{T1} = -I_{T1}Z_T = (I_{T1} - I_{B1})Z_T \quad (7)$$

It may be observed now that the cycle of operations has been established so that the next equation will be the same as eq 5 with $\dot{E}_{T1}$, $\dot{E}_{T1}$, I_{A1}, I_{B1}, or

$$\left.\begin{aligned}\frac{Z_S}{Z_S + Z_T}\dot{E}_{T1} &= \left(\frac{Z_SZ_T}{2(Z_S + Z_T)} + \frac{Z_{AA}}{2}\right)I_{A1} + \frac{Z_{AB}}{2}I_{B1}\\ \dot{E}_{T1} &= \frac{Z_{AB}}{2}I_{A1} + \left(\frac{Z_T}{2} + \frac{Z_{BB}}{2}\right)I_{B1}\end{aligned}\right\} \quad (8)$$

$$\left.\begin{aligned}I_{T1} &= -\frac{Z_S}{Z_S + Z_T}(I_{T1} + I_{A1}) + \frac{Z_T}{Z_S + Z_T}I_{T1}\\ I_{T1} &= -(I_{T1} - I_{B1})\\ \dot{E}_{T1} &= -\frac{Z_SZ_T}{Z_S + Z_T}(I_{T1} + I_{A1}) + \frac{Z^2{}_T}{Z_S + Z_T}I_{T1}\\ \dot{E}_{T1} &= -I_{T1}Z_T = (I_{T1} - I_{B1})Z_T\end{aligned}\right\} \quad (9)$$

The equations after the first may be expressed in the general form

$$\left.\begin{aligned}\frac{Z_S}{Z_S + Z_T}\dot{E}_{T(r-1)} &= \left(\frac{Z_SZ_T}{2(Z_S + Z_T)} + \frac{Z_{AA}}{2}\right)I_{Ar} + \frac{Z_{AB}}{2}I_{Br}\\ \dot{E}_{T(r-1)} &= \frac{Z_{AB}}{2}I_{Ar} + \left(\frac{Z_T}{2} + \frac{Z_{BB}}{2}\right)I_{Br}\end{aligned}\right\} \quad (10)$$

$$I_{Tr} = -\frac{Z_S}{Z_S+Z_T}(I_{T(r-1)}+I_{Ar})+\frac{Z_T}{Z_S+Z_T}I_{T(r-1)}$$

$$I_{Tr} = -(I_{T(r-1)}-I_{Br})$$

$$\hat{E}_{Tr} = -\frac{Z_SZ_T}{Z_S+Z_T}(I_{T(r-1)}+I_{Ar})+\frac{Z^2_T}{Z_S+Z_T}I_{T(r-1)}$$

$$\hat{E}_{Tr} = -Z_TI_{Tr} = Z_T(I_{T(r-1)}-I_{Br})$$

It may be observed further that eqs 1 and 2 are identical in form to eqs 5, 8, and 10 except for the terminal voltage which is the lightning potential $\hat{E}_S$. Therefore, it will be convenient to express the currents in terms of the admittances corresponding to the impedances in these equations. Designating them by Y_{AA}, Y_{BB}, and Y_{AB},

$$Y_{AA} = \frac{\frac{Z_T}{2}+\frac{Z_{BB}}{2}}{\left(\frac{Z_SZ_T}{2(Z_S+Z_T)}+\frac{Z_{AA}}{2}\right)\left(\frac{Z_T}{2}+\frac{Z_{BB}}{2}\right)-\left(\frac{Z_{AB}}{2}\right)^2}$$

$$Y_{BB} = \frac{\frac{Z_SZ_T}{2(Z_S+Z_T)}+\frac{Z_{AA}}{2}}{\left(\frac{Z_SZ_T}{2(Z_S+Z_T)}+\frac{Z_{AA}}{2}\right)\left(\frac{Z_T}{2}+\frac{Z_{BB}}{2}\right)-\left(\frac{Z_{AB}}{2}\right)^2} \quad (12)$$

$$Y_{AB} = -\frac{\frac{Z_{AB}}{2}}{\left(\frac{Z_SZ_T}{2(Z_S+Z_T)}+\frac{Z_{AA}}{2}\right)\left(\frac{Z_T}{2}+\frac{Z_{BB}}{2}\right)-\left(\frac{Z_{AB}}{2}\right)^2}$$

$$I_{A1} = Y_{AA}\frac{Z_T}{Z_S+Z_T}\hat{E}_S$$

$$I_{B1} = Y_{AB}\frac{Z_T}{Z_S+Z_T}\hat{E}_S$$

$$I_{T1} = \frac{2E_S}{Z_S+Z_T}-\frac{Z_S}{Z_S+Z_T}I_{A1} = \frac{Z_S}{Z_S+Z_T}\left(\frac{2\hat{E}_S}{Z_S}-I_{A1}\right) \quad (13)$$

$$I_{T1} = I_{B1}$$

$$\hat{E}_{T1} = Z_TI_{T1}$$

$$\hat{E}_{T1} = -Z_TI_{T1} = -Z_TI_{B1}$$

$$I_{A2} = Y_{AA}\frac{Z_S}{Z_S+Z_T}\hat{E}_{T1}+Y_{AB}\hat{E}_{T1}$$

$$I_{B2} = Y_{AB}\frac{Z_S}{Z_S+Z_T}\hat{E}_{T1}+Y_{BB}\hat{E}_{T1}$$

$$I_{T2} = -\frac{Z_S}{Z_S+Z_T}(I_{T1}+I_{A2})+\frac{Z_T}{Z_S+Z_T}I_{T1} \quad (14)$$

$$I_{T2} = -(I_{T1}-I_{B2})$$

$$\hat{E}_{T2} = -\frac{Z_SZ_T}{Z_S+Z_T}(I_{T1}+I_{A2})+\frac{Z^2_T}{Z_S+Z_T}I_{T1}$$

$$\hat{E}_{T2} = -Z_TI_{T2} = Z_T(I_{T1}-I_{B2})$$

$$I_{Ar} = Y_{AA}\frac{Z_S}{Z_S+Z_T}\hat{E}_{T(r-1)}+Y_{AB}\hat{E}_{T(r-1)}$$

$$I_{Br} = Y_{AB}\hat{E}_{T(r-1)}+Y_{BB}\hat{E}_{T(r-1)}$$

$$I_{Tr} = -\frac{Z_S}{Z_S+Z_T}(I_{T(r-1)}+I_{Ar})+\frac{Z_T}{Z_S+Z_T}I_{T(r-1)}$$

$$I_{Tr} = -(I_{T(r-1)}-I_{Br})$$

$$\hat{E}_{Tr} = -\frac{Z_SZ_T}{Z_S+Z_T}(I_{T(r-1)}+I_{Ar})+\frac{Z^2_T}{Z_S+Z_T}I_{T(r-1)}$$

$$\hat{E}_{Tr} = -Z_TI_{Tr} = Z_T(I_{T(r-1)}-I_{Br})$$

The complete solution for I_A and I_B is

$$I_A = \Sigma^rI_{Ar}$$

$$I_B = \Sigma^rI_{Br} \quad (16)$$

each term being added at the beginning of its period. Expressions for the other currents are similar.

Appendix II—Method of Calculating Protection Level

(11) In this example the counterpoise wires are considered at ground level; they consist of 2 No. 2/0 B.&S. gauge wires 50 ft apart extending parallel to the line in both directions, and 2 No. 2/0 wires at right angles 50 ft apart but extending only in one direction. This latter connects to the parallel counterpoise of another line 200 ft away, but its mutual surge impedance with the first line has been ignored. The ground plane is assumed to be 200 ft below the earth's surface. The ground wires consisting of two $^5/_8$-in. steel cables 50 ft apart average 298 ft above the ground plane. The corona radius of the ground wires for the maximum potentials encountered will be approximately 1 ft, and the geometrical mean radius of the ground wires taking into account corona and their spacing will be approximately 3.3 ft. The same corona radius is assumed for the counterpoise wires and their geometrical mean radius is approximately 2.87 ft. The geometrical mean distance between ground wires and line wires is 46.9 ft, between ground wires and counterpoise 103.3 ft, and between line wires and counterpoise 68.4 ft. It is assumed that the normal tower footing surge impedance is 400 ohms. In these calculations K is assumed equal to 4 which is believed to be a conservative value, and S is taken equal to 1.

(12) To obtain the value of m

$$Z_G = 400 \text{ ohms}$$

$$Z_1 = 60 \log_e \frac{400}{2.87} = 298$$

It is desired also to include with the ground resistance the effect of a cross counterpoise having a surge impedance equal to $Z_{12} = Z_1/\sqrt{K} = 149$ ohms. This will be denoted by Z'_G.

(13)
$$Z'_G = \frac{400 \times 149}{549} = 108.5 \text{ ohms}$$

Therefore

$$m = \frac{Z_1}{2Z'_G} = \frac{298}{217} = 1.375$$

Taking $S = 1$

$$\frac{(1+S)\sqrt{K}-S}{m+\sqrt{K}} \cdot \frac{1}{\sqrt{K}} = \frac{3}{3.375} \cdot \frac{1}{2} = 0.444$$

(14)
$$Z_{11} = 60 \log_e \frac{596}{3.3} = 312$$

$$Z_{22} = 30 \log_e \frac{400}{2.87} = 149$$

$$Z_{12} = 0.444 \times 60 \log_e \frac{498}{103.3} = 0.444 \times 94.4 = 42$$

$$Z_{13} = 0.60 \log_e \frac{559}{46.9} = 149$$

$$Z_{23} = 0.444 \times 60 \log_e \frac{461}{68.4} = 0.444 \times 114.5 = 50.9$$

From these the following are obtained:

(15)
$$Z_{AA} = 156 \text{ ohms}$$

$$Z_{BB} = \frac{74.5 \times 108.5}{183.0} = 44.2$$

$$Z_{AB} = 21$$

$$Z_{AC} = 74.5$$

$$Z_{BC} = 25.45$$

(16)
$$\frac{Z_{AA}}{2} = 78 \qquad \frac{Z_S}{Z_S+Z_T} = \frac{2}{3}$$

$$\frac{Z_{BB}}{2} = 22.1 \qquad \frac{Z_T}{Z_S+Z_T} = \frac{1}{3}$$

$$\frac{Z_{AB}}{2} = 10.5 \qquad \frac{Z_SZ_T}{Z_S+Z_T} = 66.67 \text{ ohms}$$

$Z_S = 200$ ohms

$Z_T = 100$ ohms

$\dfrac{Z_T^2}{Z_S - Z_T} = 33.33$ ohms

$\dfrac{Z_S Z_T}{2(Z_S + Z_T)} = 33.33$ ohms

$\dfrac{Z_S Z_T}{2(Z_S + Z_T)} + \dfrac{Z_{AA}}{2} = 111.33$ ohms

$\dfrac{Z_T}{2} + \dfrac{Z_{BB}}{2} = 72.1$ ohms

$\dfrac{Z_{AB}}{2} = 10.5$ ohms

$\dfrac{Z_S - Z_T}{Z_S + Z_T} = \dfrac{1}{2}\dfrac{Z_S}{Z_S + Z_T}$

$\dfrac{Z_T(Z_S - Z_T)}{Z_S + Z_T} = 33.33$ ohms

$\dfrac{2}{Z_S + Z_T} = 0.00667$ mho

Product of first 2 of above 3 quantities is $111.33 \times 72.1 = 8{,}025.0$
Square of last $= 110.2$

Difference $7{,}914.8$

$Y_{AA} = \dfrac{72.1}{7914.8} = 0.0091$

$Y_{BB} = \dfrac{111.33}{7914.8} = 0.0141$

$Y_{AB} = -\dfrac{10.5}{7914.8} = -0.00133$

For the calculations an arbitrary value $\dot{E}_S = 1{,}000{,}000$ volts will be taken. $\dfrac{2E_S}{Z_S} = 10{,}000$ amp.

$\dfrac{Z_T}{Z_S + Z_T}\dot{E}_S = 333{,}333$ volts

$I_{A1} = 3{,}030$ amp

$I_{B1} = -444$ amp

$I_{T1} = 6{,}667 - 2{,}020 = 4{,}647$ amp

$I_{T1} = -444$ amp

$\dot{E}_{T1} = 464{,}700$ volts

$\dot{E}_{T1} = 44{,}400$ volts

$\dfrac{Z_S}{Z_S + Z_T}\dot{E}_{T1} = 29{,}600$

$I_{A2} = 269.5 - 618$	$= -348.5$
$I_{B2} = -39.4 + 6{,}560$	$= +6{,}520.6$
$I_{T2} = -\frac{2}{3}(-222 - 349.5)$	$= 381$
$I_{T2} = -(4{,}647 - 6{,}520.6)$	$= 1{,}873.6$
$\dot{E}_{T2}$	$= 38{,}100$
$\dot{E}_{T2}$	$= -187{,}360$
$\dfrac{Z_S}{Z_S + Z_T}\dot{E}_{T2}$	$= -125{,}000$
$I_{A3} = -1{,}139 - 50.7$	$= -1{,}189.7$
$I_{B3} = +166.3 + 537$	$= +703.3$
$I_{T3} = -\frac{2}{3}(936.8 - 1{,}189.7)$	$= 168.5$
$I_{T3} = -(381 - 703.3)$	$= 322.3$
$\dot{E}_{T3}$	$= 16{,}850$
$\dot{E}_{T3}$	$= -32{,}230$
$\dfrac{Z_S}{Z_S + Z_T}\dot{E}_{T3}$	$= -21{,}480$
$I_{A4} = -195 - 22.4$	$= -217.4$
$I_{B4} = +28.6 + 237.5$	$= +266.1$
$I_{T4} = -\frac{2}{3}(161.2 - 217.4)$	$= 37.5$
$I_{T4} = -(168.5 - 266.1)$	$= 97.6$
$\dot{E}_{T4}$	$= 3{,}750$
$\dot{E}_{T4}$	$= -9{,}760$
$\dfrac{Z_S}{Z_S + Z_T}\dot{E}_{T4}$	$= 6{,}520$
$I_{A5} = -59.3 - 5.0$	$= 64.3$
$I_{B5} = +8.7 + 52.8$	$= +61.5$
$I_{T5} = -\frac{2}{3}(488 - 64.3)$	$= 10.35$
$I_{T5} = -(37.5 - 61.5)$	$= 24.0$
$\dot{E}_{T5}$	$= 1{,}035$
$\dot{E}_{T5}$	$= -2{,}400$
$\dfrac{Z_S}{Z_S + Z_T}\dot{E}_{T5}$	$= -1{,}600$
$I_{A6} = -14.5 - 1.4$	$= -15.9$
$I_{B6} = +2.1 + 14.6$	$= 16.7$
$I_{T6} = -\frac{2}{3}(12 - 15.9)$	$= 2.6$
$I_{T6} = -(10.35 - 16.7)$	$= 6.35$
$\dot{E}_{T6}$	$= 260$
$\dot{E}_{T6}$	$= -635$
$\dfrac{Z_S}{Z_S + Z_T}\dot{E}_{T6}$	$= -423$
$I_{A7} = -3.8 - 0.35$	$= -4.15$
$I_{B7} = +0.56 + 3.66$	$= 4.22$
$I_{T7} = -\frac{2}{3}(3.17 - 4.15)$	$= 0.655$
$I_{T7} = -(2.6 - 4.22)$	$= 1.62$
$\dot{E}_{T7}$	$= 65.5$
$\dot{E}_{T7}$	$= -162$
$\dfrac{Z_S}{Z_S + Z_T}\dot{E}_{T7}$	$= -108$
$I_{A8} = -0.98 - 0.081$	$= -1.07$
$I_{B8} = 0.14 + 0.92$	$= 1.06$

DATA OBTAINED BY CALCULATIONS

$I_{A1} = 3{,}030$ amp	$I_{B1} = -444$	$Z_{AA} = 156$ ohms	$Z_{AC} = 74.5$ ohms
$I_{A2} = -349$	$I_{B2} = 6{,}521$		
$I_{A3} = -1190$	$I_{B3} = 703$	$Z_{BB} = 44.2$	$Z_{BC} = 25.45$
$I_{A4} = -217$	$I_{B4} = 266$	$Z_{AB} = 21.0$	
$I_{A5} = -64$	$I_{B5} = 61$		
$I_{A6} = -16$	$I_{B6} = 17$		
$I_{A7} = -4$	$I_{B7} = 4$		
$I_{A8} = -1.0$	$I_{B8} = 1.0$		

The tabulated results of carrying out the additions to obtain I_A, I_B, $\dot{E}_A$, $\dot{E}_B$, $\dot{E}_C$, and $\dot{E}_A - \dot{E}_C$ are given in Table II. It may be seen that for a stroke of 20,000,000 volts the maximum value of

$\tilde{E}_A - \tilde{E}_C$ which is 20 times the value given in the table will be 2,000,000 volts reached in 1 μsec which is reduced to approximately 1,140,000 volts at the end of 2 μsec. Taking a time lag of 3 μsec and using Fig. 2, it is found that the number of standard insulators required to withstand the voltage is between 17 and 18.

Table II

Values Obtained Are Per 1,000 Kv of Stroke Potential

	Amperes		Kilovolts			
t	$\tilde{I}_A$	$\tilde{I}_B$	$\tilde{E}_A$	$\tilde{E}_B$	$\tilde{E}_C$	$\tilde{E}_A - \tilde{E}_C$
0	0.	0.	0.	0.	0.	0
0.1	303.	−44.	46.	4.	21.	25
0.2	571.	563.	101.	36.	57.	44
0.3	720.	1,241.	139.	70.	85.	54
0.4	847.	1,946.	173.	104.	113.	60
0.5	969.	2,557.	207.	138.	140.	67
0.6	1,088.	3,369.	241.	172.	167.	74
0.7	1,207.	4,082.	274.	206.	194.	80
0.8	1,326.	4,750.	307.	238.	220.	87
0.9	1,445.	5,463.	340.	272.	246.	94
1.0	1,566.	6,225.	375.	308.	275.	100
1.1	1,349.	7,087.	359.	341.	281.	79
1.2	1,174.	7,035.	332.	336.	266.	65
1.3	1,130.	6,987.	323.	332.	262.	61
1.4	1,100.	6,929.	317.	330.	258.	59
1.5	1,097.	6,866.	315.	327.	257.	59
1.6	1,084.	6,791.	312.	323.	254.	58
1.7	1,072.	6,720.	308.	319.	251.	57
1.8	1,068.	6,649.	306.	316.	249.	57

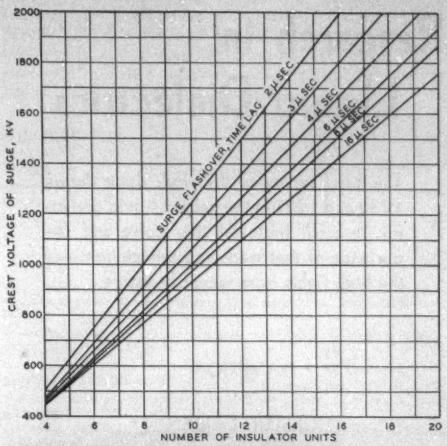

Fig. 2. Characteristics of standard 10-in. diam. insulator units with 5¾ in. spacing, 1½ × 40-μsec positive wave

Corrected to the following atmospheric conditions: absolute humidity, 6.5 grains per cu ft; relative density, 1.0

Roseland Switching Station Which May Be Visited During the Winter Convention

Among the many points in and near New York City which may be visited by those attending the winter convention of the Institute, January 23–26, 1934, is the Roseland switching station of the Public Service Electric and Gas Company of New Jersey. The 220-kv section is shown above on the left, and 132-kv section on the right

Research in Liquid Dielectrics

This brief survey of the work done during 1932 and 1933 in the field of liquid dielectric research indicates the scope and importance of that work and reflects some of the high lights from recent literature.

By
W. F. DAVIDSON
FELLOW A.I.E.E.

THORSTEIN LARSEN
NONMEMBER

Both of the Brooklyn Edison Co., Inc., Brooklyn, N. Y.

CONTINUED PROGRESS in the field of dielectric research seems to justify an annual summary in spite of the fact that Gemant's book on liquid insulation recently has been published in the United States under the auspices of the National Research Council's committee on electrical insulation. During the past year many important papers have been published dealing with different aspects of research work on liquid dielectrics. As previously, it is the complex and difficult phenomenon of liquid breakdown that has been the subject of most investigations. This is quite natural, of course, for the ability to withstand electric stress without failure is the most important property of a liquid dielectric. Hence, it may be said that studies of other questions more fundamental in character derive their importance from the ultimate bearing which they may have upon the problem of dielectric breakdown characteristics of the liquids. Other questions such as electric conduction, space charge formation, and molecular momentum of liquid dielectrics, continue to receive attention. In the fields of chemistry and physical chemistry, there also are several notable contributions to the knowledge of insulating liquids. The accompanying bibliography, without laying any claim to completeness, gives what appear to be the most important references to the literature of the past year.

To give an outline of the research of the year in liquid dielectrics, it may be worth while to mention specifically some of the papers representing the different subjects of study. In the past there have been numerous attempts to build a hypothesis of the mechanism underlying the process of dielectric breakdown in liquids. Such attempts are, for example, those of Güntherschultze, Gemant, Böning, and others. These hypotheses or theories are founded upon the assumption of ionization in a gaseous phase, or the adsorption of ions on colloidal particles as the basic phenomenon in the breakdown process. In a recent paper written by Eisler there is an interesting attempt to explain the breakdown process in terms of static ionization of the molecules of the liquid. The possibility of such ionization has not been considered seriously before, because from the classical point of view, the fields required for such ionization are vastly higher than those present in dielectric liquids at breakdown. Also, once the necessary (homogeneous) field is attained, the liquid would break down all over at once, and such a breakdown is never observed; the spark or arc always is localized in a narrow channel. However, from the point of view of quantum mechanics, a molecule has a certain chance of becoming statically ionized, even at the lowest fields. By treating the liquid as a statistical assemblage of molecules, each with a definite probability of becoming statically ionized, it is possible to calculate the current-voltage function. The author shows how this may be used to find the breakdown voltage without actually breaking down the liquid. It is clear that these considerations apply only to liquids which, in the words of the author, are "not particularly impure." In impure liquids one finds more direct causes of dielectric failure, such as fibers and drops of water. Rebhan has made a study of the mechanism of breakdown in transformer oil containing fibers and moisture. A noteworthy conclusion of his is that fiber bridges will cause breakdown only in uniform fields.

In addition to such causes as fiber bridges and different types of secondary or direct ionization as the causes of breakdown, the possibility of the breakdown being a thermal phenomenon also has been studied during the past year by Koppelman. He finds, however, that the heating effect of the current before breakdown is insufficient.

Since Güntherschultze advanced his theory it has been generally agreed that a gaseous phase in some way is connected with the breakdown of ordinary liquid dielectrics. Other authors maintained that the gas dissolved or occluded in the liquid gives the liquid breakdown its gaseous characteristics. In the last year 2 papers by Clark have discussed the importance of dissolved gases in connection with the breakdown.

In the work by Eisler referred to in the foregoing the breakdown process was regarded as essentially a statistical phenomenon. This, of course, is nothing new. Many years ago Hayden and Eddy made a statistical study of the breakdown values for transformer oil and concluded that the fluctuations represent something inherent in the oil. And during the last year Rebhan also has treated the dispersion of breakdown values for transformer oil from a statistical point of view. He finds that the values have a Gaussian distribution and gives the number of breakdowns required to furnish a "true" mean value within certain error limits. He also discusses the factors influencing the dispersion of the breakdown values.

In later years the importance of space charges in liquids under electric stress has been recognized.

Essentially full text of a report presented to the National Research Council's committee on electrical insulation, Philadelphia, Pa., Nov. 13–14, 1933. *Not published in pamphlet form.*

The presence of such space charges was demonstrated several years ago by Whitehead and Marvin. Böning and Schaefer also did some work in connection with this problem, and during the year Gemant has made an interesting contribution to the study of space charges. He attempts to measure the charges directly by means of a ballistic galvanometer. The experimental technique is briefly as follows: In the oil to be studied (which is highly purified) small permeable containers (paper) are placed close to the electrodes. After a direct voltage of from 5 to 20 kv has been applied for several minutes, the electrodes are short-circuited and the container withdrawn. The charge on it is measured ballistically. The experiments are quite difficult to carry out. Gemant believes that he has observed saturation phenomena.

The subject of conduction in dielectric liquids again has been treated by Nikuradse in several papers. From a very thoroughgoing analysis of experimental data on conduction at high field intensities he concludes that the steep current-voltage characteristic is caused, as in gases, by impact ionization.

A Dutch author, Van Arkel, throws an interesting side light on one particular type of conduction, namely, that of very thin films of liquid hydrocarbons. As pointed out by Brüninghaus, such thin films have a very high conductivity which Van Arkel ascribes to carbon particles formed by decomposition of the oil.

The important question of oxidation of transformer oils has been dealt with in a paper by Ornstein in collaboration with others. The oxidation of an oil takes place both in the oil itself and in the gas above the oil, the former process being by far the most important in the deterioration of the oil. The authors study the absorption of oxygen by a method developed by themselves which is said to be quicker and better than those previously used. As a result of their experiments they find that after the so-called period of induction the oxidation of transformer oil can be described by a monomolecular reaction equation. The velocity constant varies with temperature in accordance with the Arrhenius formula. It is possible, then to calculate the activation energy which is found to be constant up to 115 deg C, above which temperature it decreases. As the oils deteriorate, the activation energy and the reaction constant both vary, and the authors suggest that it would be quite feasible to characterize an oil through these quantities.

The question of polymerization and disintegration of hydrocarbons under the action of electric discharges has been studied by several investigators. In addition to the work of Linder in the United States, there is that of Vanier de Saint-Aunay in France who finds that the reaction is either polymerization, dehydrogenation, or decomposition, the decomposition occurring particularly with long-chain molecules.

The foregoing brief summary suffices, perhaps, to give a picture of the manifold activities of workers in the field of liquid dielectrics during the past year. The complete story, of course, may be had from the original papers, and it is hoped that the following bibliography does not miss too many of these. ED. NOTE: On p. 926–27 of this issue is given a further bibliography, covering the more important contributions of the past 4 years to the literature concerning the theories of dielectric research.

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Improvements in Impregnated Paper

A brief survey of improvements in impregnated paper cable insulation as revealed by operating records of the Commonwealth Edison Company, Chicago, covering a period of 14 years is given here. Tangible savings resulting from improved insulation are shown to appear importantly in the dollars-and-cents columns of the operating records.

By
D. W. ROPER
FELLOW A.I.E.E.

Commonwealth Edison Co., Chicago, Ill.

ACCORDING to a paper presented to the A.I.E.E. in 1900 by Henry Floy, some 25-kv 3-conductor cable with impregnated paper insulation was installed at St. Paul in that year. The records, however, fail to disclose any increase in the operating voltage for underground cable in the United States during the next 20 years, nor do they indicate that there was any significant improvement in the quality of the insulation during that period. Hence, this brief survey will be limited to the period since 1920.

Before entering the main topic it may be well to note in passing that the use of power factor measurements for determining the quality of insulation was suggested first by Rayner in a paper to the British I.E.E. in 1912. Wallace Clark confirmed this method in his discussion following the presentation of the Clark-Shanklin 1917 paper on single conductor cable, and Farmer presented a paper on such measurements to the A.I.E.E. in 1918. Since then the power factor method of comparing the quality of insulation has been quite generally used.

For the purpose of this survey, fairly complete records of about 1,100 miles of 13-kv 3-conductor cable purchased in 1920 and succeeding years are available and will be utilized. The power factor tests on individual samples of cable made about the beginning of this period are shown in Fig. 1, which is taken from my paper before the A.I.E.E. in 1922, and which shows power factors ranging from about 3 to 40 per cent at 80 deg C. Tests on samples that had been in service for several years range from about 23 to about 64 per cent at 80 deg C. However, because at a temperature of about 60 deg C. or less the dielectric loss in many cases would be so great that cumulative heating with so-called dielectric loss failures would result, it was impossible to operate cables with the higher power factors at a temperature anywhere near the temperature at which the insulation might be injured by the heat. When this point was brought to the attention of the cable manufacturers they endeavored to improve the insulation by abandoning the use of the impregnating compounds formerly used (consisting of a solution of resin in resin oil, or resin in transil oil) substituting an impregnating compound which consisted principally of a mineral grease of about the consistency of vaseline and sometimes containing a moderate percentage of resin. This change resulted in a reduction in dielectric loss, but it had an adverse effect upon the insulation failure record. To determine the average power factor data shown in Fig. 3, all the test results obtained on the cables of each manufacturer were averaged to determine an average figure for each manufacturer, and then these later figures were averaged to secure the data plotted.

A few years later this type of impregnating compound was abandoned in favor of a compound consisting principally of a heavy mineral oil, similar to cylinder oil, sometimes with the addition of some resin. In succeeding years American manufacturers have shown a rather continuous tendency toward the use of lighter oils for their impregnating compounds. During this period there has been a practically continuous reduction in the dielectric loss of impregnated

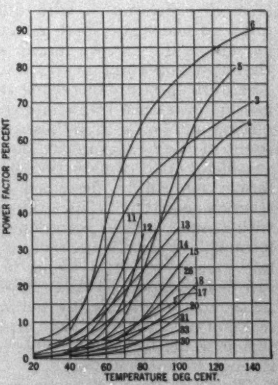


Fig. 1. Dielectric loss curves for 12-kv cables

These curves are reproduced from p. 549 of the A.I.E.E. TRANS., v. 41, 1922. The highest power factors were found in cables impregnated with resin oil compounds, the lowest losses from cables with a mineral oil compound. Intermediate curves are from cables with various mixtures of the 2 compounds

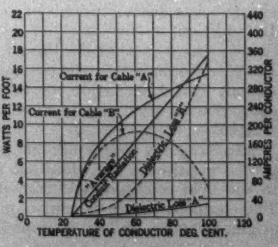


Fig. 2. Effect of reduced dielectric loss in increasing the carrying capacity of cables

These curves reproduced from p. 549 of the A.I.E.E. TRANS., v. 41, 1922

Full text of a report presented to the National Research Council's committee on electrical insulation, Philadelphia, Pa., Nov. 13–14, 1933. *Not published in pamphlet form.*

paper insulation and, marvelous to relate, it has been accompanied by an equally great improvement in the failure record. It is plain, therefore, that the improvements which the manufacturers have made in the power factor of their impregnated paper insulation in recent years have not been made at the expense of the quality of the insulation.

Some critic may say that the statement applies only to the initial quality of the insulation, but, although some indications of deterioration of the insulation have been noted, a detailed examination of the failure record (Fig. 4) shows that there has been no progressive increase in insulation failures in recent years. In Fig. 5, as well as in the later figures the power factor data shown are plotted from the average results of all tests made on the product of one manufacturer for the years shown. In the case of the data shown in Fig. 5, there was no significant change in the power factor of the insulation on cable received from the several manufacturers in the period shown, except for manufacturer *B*.

Available records permit one statement to be made in accordance with the original desires of our Chairman. The best example of improvement noted during the past year is shown in the reduction in the records of 13-kv cable received this year, in which the curve of power factor of the dielectric loss versus temperature is below the corresponding curve for oil

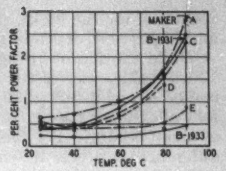


Fig. 5. Average power factors of 13-kv 3-conductor cable observed from Jan. 1, 1930, to Oct. 1, 1933

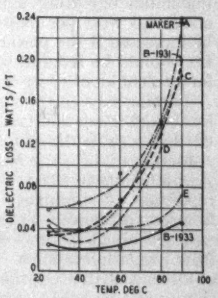


Fig. 6. Average dielectric losses of 13-kv 3-conductor cable observed from Jan. 1, 1930, to Oct. 1, 1933

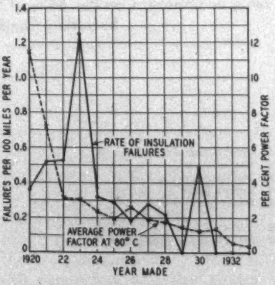
filled cable throughout the entire operating range—a truly marvelous performance and one that would have been declared impossible a few years ago. This incident indicates, if it were not already known, that due caution should be observed in connection with statements that desired improvements are impossible.

Any survey over an extended period would be incomplete if it failed to look forward and set forth what the records indicated should be the desirable course for the future.

The improvements that have been made in impregnating compounds in recent years indicate the possibility of securing compounds which will be stable at somewhat higher temperatures and stresses than those now used for 66-kv cable. Also it appears possible to devise suitable tests to be applied to cable to determine whether the insulation will be suitable for operation at these higher stresses and temperatures. With the use of such improved impregnating compounds and test methods, the maximum operating temperature of 66-kv cable, for example, might be raised to about 70 or 75 deg C, and then the limiting temperature will be determined by the lead sheath or by the design of the manholes. When such a change is made on the 66-kv cable, the maximum operating temperature of the 13-kv cable probably will be raised to about the same temperature as low voltage cables.

Some years ago, when the dielectric losses were reduced sufficiently to eliminate the possibility of dielectric loss failures, the carrying capacity of the 13-kv cables was increased about 50 per cent, resulting in a reduction of more than 30 per cent in the capital charge. When the further increases in operating temperatures as just proposed are in effect, there will be a further reduction of about 8 per cent in the capital charge for the 13-kv cables, while the

Fig. 3. An operating record of 1,085 miles of 13-kv 3-conductor cable on the system of the Commonwealth Edison Company



Year Made	Miles of Cable	Number of Insulation Failures												
		1920	'21	'22	'23	'24	'25	'26	'27	'28	'29	'30	'31	'32	'33	Total
1920	50	2														2
1921	37		1						1							2
1922	100						2	1	2							5
1923	159				2	6	1	5		2	1					17
1924	149						1			1		1		1		4
1925	98									1		1				2
1926	164									1			1			2
1927	62													1		1
1928	95									1						1
1929	53															0
1930	72											1				1
1931	48															0
1932	2															0
1933	2															0
Total	1,085	2	1	0	2	6	4	6	3	6	1	3	1	2	0	37

Fig. 4. Chart showing 14-year record of insulation failures in 13-kv 3-conductor cable

reduction for the 66-kv cables would be between 10 and 20 per cent, depending upon local conditions.

While the recent reduction in dielectric losses of 13-kv cable, expressed as a percentage, appears rather large, it amounts to less than 0.1 watt per foot of cable at the maximum operating temperature of about 80 deg. For the 66-kv cables, however, the difference between the highest and lowest values amounts to nearly 0.2 watt per foot of cable at the maximum operating temperature of 60 deg C., or about 0.5 watt per foot of *line*. This figure would be increased if the power factor of the 66-kv insulation should be reduced to the very low figure shown for a recent lot of 13-kv cable.

Turning now to the significance of these dielectric losses and insulation failures, Table I shows that for the 13-kv cable the annual saving resulting from the reduction in dielectric loss by one maker in the past year amounts to nearly five times the annual cost of repairing cable damage resulting from insulation failures; in the case of the 69-kv cable, the possible saving is about 15 times the annual charges resulting from insulation failures. Apparently, therefore, the economies of the situation indicate that more attention should be paid to the reduction in the dielectric loss; further, that this point becomes of increasing importance as the operating voltage of the cable is increased.

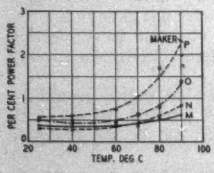


Fig. 7. Average power factors of 69-kv single-conductor cable observed from Jan. 1, 1930, to Oct. 1, 1933

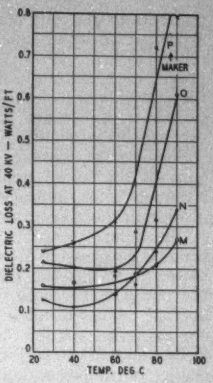
If further reductions in power factor of 66-kv insulation are accompanied by reductions in thickness of insulation, the reductions in dielectric loss expressed in watts per foot that may reasonably be expected probably will not be more than 25 per cent below the lowest values obtained to date.

Table I—Costs of Dielectric Losses and Insulation Failures

	13 kv	69 kv
Rated voltage		
A. Recent annual savings due to reduction in dielectric loss per mile of line	$4.30	$114.00
B. Annual cost of cable failures per mile of line	$0.93	$7.88
Ratio: A to B	4.6	14.5
Further increase in carrying capacity that would result from entire elimination of dielectric loss	0.4%	1.4%

Further interesting information obtained from a comparison of the total annual charges for 13-kv and 69-kv cables is given in Table II. The largest item covers interest and taxes which can be reduced by a reduction in the first cost. The depreciation item has been assumed at about 3 per cent, and it would be quite interesting if investigations now under way

Fig. 8. Average dielectric losses of 69-kv single-conductor cable observed from Jan. 1, 1930, to Oct. 1, 1933



should indicate a lower percentage to be warranted. Reduction of the maintenance figure of the 69-kv cable so that it would be no greater than the corresponding figure for 13-kv is an interesting prospect, but beyond the scope of this present discussion. The records indicate that a reduction of the insulation losses is perfectly feasible.

Table II—Annual Cost Per Mile of Line of Installed Cable, Excluding Conduit

	Item	Per Cent of Total: 13-Kv 3-Cond. 500,000 Cir Mils	Per Cent of Total: 69-Kv 1-Cond. 750,000 Cir Mils
1	Interest and taxes	53.0	51.9
2	Depreciation	18.7	18.4
3	Maintenance	3.0	8.3
4	Copper losses	24.8	19.1
5	Insulation losses	0.5	2.3
6	Total	100.0	100.0
7	Fixed charges (sum of items 1 and 2)	71.7	70.3

Returning to the item of first cost, the records indicate that a moderate reduction can be made if the manufacturers will utilize all recent improvements in the quality of the insulation to reduce its thickness, rather than to attempt further reductions in the present low failure records. Another method of reducing the first cost is by devising new types of cable for the higher voltages; with this end in view 5 distinct new types have been proposed in the United States and abroad within the past few years. During this same period new methods of testing cable and, what probably is more important, improved methods of examining insulation after test or after years of service to determine the nature and extent of the changes in the insulation have been devised and are available for prospective purchasers in determining the merits of the new types of cable as compared to the types now in common use. Although available information regarding these new

types of cable is rather meager, the indications are that, although some of them may be found advantageous and economical for European conditions, the solid type of insulation for voltages up to 66 kv, and the oil filled type of insulation for higher voltages, probably will prove to be the most economical for Chicago conditions.

Improvements in Solid Dielectrics

This brief survey of some of the important work done during the past year in the field of solid dielectrics, touches upon the evolution of the pyroelectric theory of breakdown and recounts some of the significant developments in modern rubbers. Other high lights are reflected from recent literature.

By
R. W. ATKINSON
FELLOW A.I.E.E.

General Cable Corp., Perth Amboy, N. J.

IN PRESENTING this summary of the year's progress in electric research for solid insulation, proportionately more space has been given to European publications than to American, because of the relative availability of this literature. Also, to permit a reasonably full exposition of a few topics, others necessarily have been condensed to but little more than descriptive titles.

Important New Properties of Rubber

Both because of the outstanding importance of the dielectric concerned and because of the sweeping nature of the development, a description of the new qualities which have been imparted to rubber and rubber-like dielectrics should be foremost in any description of the advancement in solid dielectrics. While important information on the subject is given in some publications of the U. S. Bureau of Standards, in certain manufacturers' trade publications, and even in some of the newer specifications, the commercial developments in rubber have proceeded far beyond anything that is realized by any except those closely in touch with the laboratories of the manufacturers concerned. Hence, full knowledge of the advancement in rubber insulation must go beyond published information. In general, the term "rubber" as here used applies to any completed insulating material which includes crude rubber or caoutchouc in its composition.

Before describing the nature of the developments in rubber insulation, it is proper to say a word concerning the reason for the sudden and rapid development in this, one of the oldest of the important commercial insulating materials. Rubber is perhaps the earliest insulating material on which an adequate specification was produced, and that specification was based primarily upon the composition and the chemical analysis of the material rather than upon the performance of the resulting product. While the specification was an important and valuable safeguard at the time of its inception, the result was, as is fundamental with this type of specification, the fixation of properties in the existing form and the stifling of development. With the development of materials having markedly better performance than the materials covered by the older specifications but incapable of meeting the rigid chemical requirements of those specifications, came the development of the new type of specification—the performance type. With the field open for commercial exploitation of the new properties, there has been a rapid further development of rubber insulation.

Some of the ways in which properties of rubber have been modified in noteworthy manner are touched upon in the following items:

1. Stability has been improved under conditions usually producing short life of rubber, such as high temperature, exposure to oxygen and to ultra-violet light, or a combination of these. The life at a given high temperature has been multiplied by from two to many times for different types of the new materials. By way of further example, older types of rubber compounds are deteriorated completely by exposure for one day to a current of air at 250 deg F, whereas newer types after 4 days of this treatment still meet all the *original* requirements of the older specification. Some of these newer materials will withstand operating temperatures of from 15 to 30 deg C higher than will produce early destruction of the older types of rubber.

2. The ability of some of the new rubbers to withstand ozone cutting is enormously better than for the older types.

3. The dielectric constant of rubber now may be controlled through a wider range than before, and yet combined with other required characteristics including high resistance to moisture. Values as low as 2.6 or 2.7 are obtainable (comparable with that of the pure gum) and the customary older values of 4.5 to 6.0 are still obtainable. This is important in several ways. The very low values of dielectric constant, which can be combined with very low dielectric losses, are important for cables for signal and telephone transmission. When rubber with a low value of dielectric constant is used for high voltage power use, the lower dielectric constant results in lower stress in the air surrounding the rubber and is a direct means of avoiding corona difficulties. Thus, the ozone cutting just described may be avoided by the use of low dielectric constant, by ozone resisting material, or by a combination of these. The wide range of dielectric constants now available permit the use of grading, long discussed theoretically, but only recently available in rubber or other cable insulation.

4. Whereas rubber definitely required protection from oils and most acids and alkalis, certain rubber or rubber-like materials now available may be subjected to oil or to usual acids or alkalis without damage.

5. Along with these changes have been relatively smaller but still

Essentially full text of a report presented at the National Research Council's committee on electrical insulation, Philadelphia, Pa., Nov. 13-14, 1933. *Not published in pamphlet form.*

very important improvements in dielectric strength and in dielectric loss.

Rubber as a commercial insulating material always has consisted of a certain proportion of rubber vulcanized with sulphur and combined or "compounded" with various fillers. In the past, as required by specifications, these have been almost exclusively dry mineral matter. More recent developments have come about by the addition of various accelerators, antioxidants, and new types of fillers. Some of the more important of these fillers are various vulcanized oils. Some of the special properties are now secured by the use of a very large proportion of rubber hydrocarbons that would have been exceedingly expensive in the earlier days of higher priced crude rubber.

While all the outstanding advancements mentioned have been obtainable with materials based primarily upon the crude rubber of commerce, still further improvements in some particulars have been secured by the use of new synthetic and rubber-like compounds. In general, the newer synthetic materials do not have electrical characteristics as good as the natural rubber compounds have, but they can be made to have even greater resistance to heat, ozone, oils, acids, alkalis, and moisture. In view of this, some of the greatest improvements in commercial products such as cable insulation have been effected by the use of a major portion of rubber insulation protected by final layers containing the newer synthetic hydrocarbons such as thiokol, sometimes (incorrectly) referred to as synthetic rubber. Duprene is another rubber-like material which possesses highly valuable properties, such as exceptional oil resistance.

Not all the properties enumerated have been improved in equal degree in any particular type of rubber-like material now commercially available. Hence, different "rubbers" are used for different specific purposes such as resistance to heat, moisture, corona, oil, or for low dielectric constant, although several of the more important properties frequently are combined in a notable degree. Future development no doubt will increase the ability to combine various desirable characteristics in the highest degree, as well as lead to further improvement in these specific characteristics. Advancement in the characteristics of rubber insulation have been so rapid that the users or potential users of rubber insulation have not yet realized or taken advantage of the new characteristics.

Pyroelectric Theory

Dr. K. W. Wagner in his paper on "Properties of Insulating Materials and Their Measurement" presented before the International Electrical Congress, Paris, 1932, again emphasized the "pyroelectric theory" of dielectric failure which aroused so much interest when presented by him before the A.I.E.E. convention at Chicago in 1922. ("The Physical Nature of the Electrical Breakdown of Solid Dielectrics," A.I.E.E. Trans., v. 41, 1922, p. 288–99.) As originally presented, it was generally understood that Dr. Wagner explained practically all dielectric stress failures by assuming a path through the insulation of somewhat higher conductivity than the average. This conductivity results in an increase in current through such a path, creating heat which must be dissipated into the surrounding material or by conduction to the electrodes. The increase in temperature results in still higher conductivity. If the heat can be conducted to the surroundings as fast as it is being generated the "thermoelectric equilibrium" remains stable. When the opposite is true, an unstable condition results and cumulative heating occurs until rupture takes place. Although still putting principal emphasis on this theory, Dr. Wagner in his recent paper states that breakdown may result from ionization by collision. He points out that rupture most nearly approaches this phenomenon in pure materials with low losses (crystals, for example) or for ordinary insulating materials at low temperatures or under very high stress.

It seems important to define accurately the condition to be called dielectric loss of pyroelectric failure. If a homogeneous solid dielectric having dielectric loss be conceived, thermal insulating conditions which will result in pyroelectric failure for any specified impressed dielectric stress may be defined. This is the cumulative heating discussed widely for cables, especially since the Bang & Louis A.I.E.E. paper of 1917. The fact that no dielectric is perfectly uniform, and that some path will reach the point of cumulative heating before the remainder, merely localizes final failure, but unless there are major nonuniformities in dielectric loss, does not change materially the voltage at which failure would have taken place.

The moving cause of pyroelectric failure is the dielectric loss rather than the nonuniformity of the dielectric. If, as some claim, nonuniformity is important the terms must be defined very clearly; otherwise any failure may be regarded as pyroelectric. For example, disruptive failure of a gas, being caused by the high velocity of local ionized particles, may be regarded as pyroelectric because the high velocity may, in effect, be considered as high temperature. Therefore, microscopic or submicroscopic nonuniformities should be distinguished clearly from those having an area of such dimensions as to be comparable with the insulation thickness. Failure then would be defined as pyroelectric only where the dielectric loss characteristics of the material as a whole or of substantial subdivisions are such as to produce cumulative heating as a result of more production than dissipation of heat. Only under such a definition may a useful distinction be drawn between pyroelectric and other failures. Contrary to Wagner's view that most failures are pyroelectric, it seems clear that under any such definition many observed data fall into a classification other than pyroelectric. In any particular case the distinction usually can be made clearly.

The principal part of Dr. Wagner's paper is devoted to the behavior of insulating materials under stresses well below the point of failure. Starting from the statement that the departure in behavior of solid dielectrics from that of the so-called

"ideal dielectric" may be explained on the basis of nonhomogeneity in structure, he presents a theory using a mechanism somewhat different from the classical method of Maxwell which assumed a dielectric made up of layers of different "ideal dielectrics." Wagner postulates a principal "ideal dielectric" in which little spheres of a second "ideal dielectric" are distributed irregularly. He also has considered the case where the second dielectric itself is composed of several materials, and has calculated formulas to apply to such materials. He also obtains formulas showing the way in which frequency and temperature affect the dielectric constants.

The paper also discusses the theories as applied to other classes of dielectrics. The treatment of fibrous materials is based on Evershed's work and assumes that there is in the tubular spaces between the fibers "alternately bubbles of air and drops of water" with the air bubbles surrounded by a film of water. These enclosing films contract under electrical stress and produce a reduction in the effective resistance of the system. Because of inertia there also appears the phenomenon of hysteresis. In the same way may be explained the increase in losses when the voltage increases. Because of the inertia of the movement of water, this increase always is less at very high frequencies.

These physical theories should be considered in connection with those which have been much discussed in previous meetings of the N.R.C. committee on electrical insulation and which postulate rotating ionized molecules or masses or the movement of space charges through the body of the dielectric.

Dr. Wagner also urged the importance of studying the phenomenon of luminescence in solid and liquid insulating materials. Until very recently the study of this type of phenomena has been limited to air, but it is known that such phenomena do appear in some liquid and solid insulations. In some cases these have been explained by the presence of air included in the materials, but materials undoubtedly without air (for example, degasified oil) also present luminesce phenomena with fields of very high intensity. Means for making such studies in solids are offered by the electrocamera of Gemant.

Probability in Electrical Breakdown

A paper by R. Wideroe ("Dielectric Strength of Solid Insulation," *Archiv fur Elektrotechnik*, 1932, v. 26, p. 626) seeks to reconcile various existing theories of electrical breakdown by the introduction of probability.

The rupture theory of electrical breakdown explains a failure on the basis that the molecules of the insulators are ruptured when the electrostatic force of the electrical field overcomes the cohesive forces of the ions in the molecules. According to calculations of Rogowski some years ago, the voltage required to produce such a field is of the order of 10^8 volts per cm, which is about 100 times the highest values obtained practically up to that time. According to this theory, breakdown strength is independent of insulation thickness.

Ionization by collision theory has two versions, one of which may be designated as Rogowski's theory and the other as Joffé's theory.

Rogowski's explanation is that through action of the field the electron attains so high a velocity, particularly in the submicroscopic cracks of the lattice, that it is enabled to break a lattice band and thus start the failure. According to this theory, the failure is not caused by a gradually increasing stream of electrons, but is caused by the breaking of one ion band, which breaking must be regarded as the primary cause from which the electron stream and other phenomena develop. Here also dielectric strength would appear to be independent of thickness of insulation.

Joffé's explanation is that failure occurs only when the electron flow resulting from ionization by collision reaches a certain definite value. Thus, a stronger field is required to produce failure in thin than in thick dielectrics. In fact, Joffé has found that breakdown strength increases enormously for very thin films; for electrode separations of less than 10^{-4} cm he reached values in excess of 10^8 volts per cm. He estimates that for a thickness of less than 0.2×10^{-4} cm the value calculated according to the rupture theory would be reached.

Wideroe points out that the discrepancy between the rupture theory and Joffé's theory may be bridged over if the rupture theory be regarded as the limiting condition of Joffé's theory. Thus, the point of molecular instability will change with thickness of insulation and, with a sufficiently great thickness, a sufficient number of electrons can be freed at the point of initial ionization to cause failure.

Wideroe suggests as a plausible hypothesis that if μ designates the probability that failure will be caused by a single overstepping of the lattice energy, $1/\mu$ molecules must be ruptured before the probability of failure is 1. This corresponds *approximately* with Joffé's assumptions. However, it may be considered that before a molecule can be ruptured the ion must be struck in a certain definite direction or by an especially direct impact, and that only in one collision out of $1/\mu$ does such an impact occur. This would satisfy Rogowski's physical theory. Mathematically these are identical.

Wideroe calculates the energy which would be required to break a rock salt crystal molecule and then derives a formula for the stress required to produce failure, according to which formula the stress is a function of the thickness of insulation and μ. He constructs curves for rock salt with $\mu = 1$, $1/10$ and $\mu = 1/100$, and on the same curve sheet plots values for rock salt obtained by Güllner for thicknesses of from 0.006 to 0.03 cm. The calculated values are found to be from 50 to 100 per cent higher than those observed, depending upon the value of μ. As no experimental values are available for very small thicknesses, no idea of the values of μ for rock salt can be obtained.

He also plots values obtained by Joffé and Güllner for mica and other substances of thicknesses varying from 9×10^{-5} to 0.9×10^{-2} cm, to which he fits a curve. He finds that this curve corresponds to $\mu = 1/70$ for mica, and suggests that μ in all cases

lies between 1/10 and 1/100. This corresponds very well with Rogowski's conclusion that in gases only about 2 per cent of those molecules which have sufficient energy actually become ionized.

Weatherproof Wire and Other Items

In the field of "weatherproof" insulated wire, a condition somewhat analogous to that described for rubber exists. The story is summarized in a report of a research by Purdue University under the auspices of the Utilities Research Commission. A new specification has recently been agreed upon between the Utilities and the manufacturers who have followed this project. A large amount of weatherproof insulated wire has been purchased over a considerable period of time which meets these requirements and which is a far more dependable and lasting insulation than material made according to previous standards.

Schumann, studying the conductivity in a solid dielectric transverse to the direction of the main electric field, has found indications that the conductivity normal to the main field may be constant, but surely does not vary as much with field stress as does the conductivity in the direction of the field. Von Philippoff has made oscillographic studies of a current through a dielectric approaching failure of the pyroelectric type. The more important information developed by this method has to do with the wave shape of the current as failure is approached. He defines a distortion of wave form which he says is similar to a hysteresis effect, and which he discusses on theoretical grounds.

Associates of Moon and Norcross have published in the A.I.E.E. Transactions an extension of their earlier paper showing the existence of an intermediate region of breakdown between the thermal and electrical. Although the new work is performed with alternating current whereas the former being done with direct current, the intermediate region is found to exist as before. However, Inge and Walther in the *Ark. Elek.* publish an experimental investigation of this matter and conclude that no such intermediate region exists. This interesting subject merits continued study.

On subject of insulator sparkover as affected by dirt, moisture, and power frequency or transient voltages a good many articles have been published, mostly in the A.I.E.E. publications.

Further work of Whitehead and his associates on the relation between d-c and a-c characteristics of insulation, and the relation between the electrical properties of oil and paper separately and in combination, has been published. Whitehead also shows the voltage breakdown of saturated paper samples in relation to the physical characteristics of the saturating oil, particularly viscosity and surface tension.

Race gives data on capacitance and loss variations with frequency and temperature, in composite insulation. He discusses these data theoretically showing that the general form of these characteristics could be caused by any one of several physical mechanisms and indicates that, in laminated products of synthetic resin, the observed characteristics may reasonably be represented physically and mathematically by the Maxwell-Wagner theory.

J. A. Scott shows the effect of high oil pressure upon the electrical strength of cable insulation.

Four-Year Bibliography

The following references embrace most of the better known publications and cover most articles that have appeared dealing with theories of dielectric phenomena or with data on specific dielectrics where such data have reference to the subject of dielectric phenomena as a whole. The entries in this bibliography cover the 4-year period 1930–33 and are intended to supplement and bring up to date for general reference purposes the bibliography on "Theories of Dielectric Phenomena" published on p. 363–65 of the N.E.L.A. *Underground Systems Reference Book.*

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News
Of Institute and Related Activities

Technical Program for Winter Convention Announced

THE technical program for the forthcoming winter convention of the A.I.E.E. to be held in the Engineering Societies Building, 33 West 39th Street, New York, N. Y., during the 4 days of January 23–26, 1934, is being prepared as usual to present to the engineering profession the most recent developments in electrical engineering, and to lay the groundwork for future trends. The technical program tentatively arranged for this convention is presented herein.

As announced in ELECTRICAL ENGINEERING for November 1933, p. 795, the 1934 winter convention will differ from other recent winter conventions in that it will start on a Tuesday, one day later in the week than before, and will last but 4 days. Technical sessions will be held Tuesday to Thursday, with inspection trips on Friday. For the evenings, a smoker probably will be arranged for Tuesday, the Edison Medal presentation for Wednesday night, and the dinner-dance for Thursday night. Further details of these features and of special plans which are being made for the women will be announced in the January 1934 issue of ELECTRICAL ENGINEERING. The membership of the general convention committee was announced in the November issue. Chairmen of the various subcommittees are as follows: executive committee, C. R. Beardsley, Brooklyn Edison Company, Brooklyn, N. Y.; dinner-dance committee, George Sutherland, New York and Queens Electric Light and Power Company, Flushing, N. Y.; smoker committee, R. A. McClenahen, United Engineers and Constructors, Inc., Newark, N. J.; inspection trips committee, H. C. Otten, United Electric Light and Power Company, New York, N. Y.; and the ladies' entertainment committee, Mrs. H. R. Woodrow, Brooklyn, N. Y.

TECHNICAL SESSIONS

Interest in the 10 technical sessions which have been scheduled in the mornings and afternoons of the first 3 days of the convention should be stimulated by the fact that the majority of papers to be discussed at these sessions already will have been distributed to the entire membership through the columns of ELECTRICAL ENGINEERING. Those attending the sessions will thus be better prepared to understand and discuss the subjects than was possible previously, and at many of the sessions more time for discussion also will be available. In the November 1933 issue 4 of the 1934 winter convention papers were included, and 14 are contained in the present issue. In so far as they are made available, the remainder of the winter convention papers will be in the January 1934 issue.

The first of the 3 symposiums which are included on the accompanying technical program is that on switching at modern large generating plants. These papers have been selected not only so as to indicate the different practices in widely separated parts of the United States, but also to indicate practices which were in vogue at different times during the past several years. From these papers, 2 of which are included in this issue, operating practice and trends in design for such plants may be determined.

The symposium on long distance transmission and reproduction in auditory perspective of symphonic music should be of particular interest not only to communication engineers, but to all technically trained individuals. The desire for further information on this subject has been particularly widespread since the recent World's Fair in Chicago, at which auditory perspective was used in several striking demonstrations. The work done by one of the leading orchestral conductors in this country in the satisfactory reproduction of music also has contributed to this widespread interest.

The symposium on electric furnaces is intended to bring out the design and operation of various types of these furnaces and of related equipment. They are considered from the various points of view of the manufacturer, metallurgist, and the central stations supplying the energy. The papers which are tentatively scheduled for these 3 symposiums and the 7 other technical sessions are listed herewith:

Tentative Technical Program

Tuesday, January 23

9:00 a.m.—Registration

10:00 a.m.—Opening of Convention

10:30 a.m.—Protective Devices

PETERSON COIL TESTS ON 140-KV TRANSMISSION SYSTEM, J. R. North, The Commonwealth and Southern Corp., and J. R. Eaton, Consumers Power Co.

LIGHTNING POTENTIALS MEASURED ON 4,000-VOLT OVERHEAD CIRCUITS, Herman Halperin, Commonwealth Edison Co., and K. B. McEachron, General Electric Co.

AUTOMATIC CONTROL OF POTENTIAL CONNECTIONS FOR DISTANCE RELAYS, A. R. Van C. Warrington, General Electric Co.

AUTOMATIC RECLOSING OF OIL CIRCUIT BREAKERS, A. E. Anderson, General Electric Co.

10:30 a.m.—Transportation

TROLLEY WIRE LUBRICATION IMPROVED, J. V. Lamson, University of Washington.

EXPERIMENTAL INVESTIGATION OF RAIL IMPEDANCES, H. M. Trueblood and George Wascheck, American Telephone & Telegraph Co.

PANTOGRAPH TROLLEY DEVELOPMENT AND OPERATING CHARACTERISTICS, W. Schaake and B. M. Pickens, Westinghouse Electric & Mfg. Co.

2:00 p.m.—Symposium on Switching Energy at Modern Large Generating Plants

HUDSON AVENUE GENERATING STATION, C. M. Gilt, Brooklyn Edison Co.

RICHMOND GENERATING STATION, Raymond Bailey and F. R. Ford, Philadelphia Electric Co.

This a-c calculating board in the Pennsylvania Station, New York, N. Y., will doubtless be a feature of interest to many of those attending the annual winter convention of the A.I.E.E. in New York, Jan. 23–26, 1934. This calculating board is used by engineers of the Pennsylvania Railroad, and of Gibbs and Hill in solving high voltage a-c network problems relating to the supply of energy to railroads and associated equipment

LONG BEACH STEAM PLANT NO. 3 OF THE SOUTHERN CALIFORNIA EDISON CO., LTD., A. A. KRONEBERG and O. R. BULKLEY, Southern California Edison Co., Ltd., and W. A. ANDREE, Stanford University.

CONNORS CREEK GENERATING PLANT OF THE DETROIT EDISON COMPANY, A. P. FUGILL, The Detroit Edison Co.

STATE LINE STATION, CHICAGO DISTRICT ELECTRIC GENERATING CORPORATION, T. C. WHITE, Electric Generating Corp.

Wednesday, January 24

10:00 a.m.—Power Transmission and Stability

COUNTERPOISES FOR THE PROTECTION OF TRANSMISSION LINES, C. L. FORTESCUE, Westinghouse Electric & Mfg. Co.

CORONA LOSS FROM 1.4 IN. DIAMETER CONDUCTORS, J. S. CARROLL, Stanford University, and BRADLEY COZZENS and T. M. BLAKESLEE, Dept. of Water and Power, City of Los Angeles.

ATTENUATION AND DISTORTION OF TRAVELING WAVES, L. V. BEWLEY, General Electric Co.

POWER LIMITS OF 220-KV TRANSMISSION LINES, A. A. KRONEBERG, Southern California Edison Co., Ltd., and MABEL MACFERRAN, Metropolitan Water District of Southern California.

POWER LIMITS OF SYNCHRONOUS MACHINES, EDITH CLARKE and R. G. LORRAINE, General Electric Co.

STEADY STATE STABILITY OF COMPOSITE SYSTEMS, S. B. CRARY, General Electric Co.

POWER LIMIT OF A TRANSMISSION SYSTEM, W. S. PETERSON, Bureau of Power and Light of the City of Los Angeles.

2:00 p.m.—Symposium on Long Distance Transmission and Reproduction in Auditory Perspective of Symphonic Music

* FUNDAMENTAL REQUIREMENTS, H. FLETCHER, Bell Telephone Laboratories, Inc.

* AUDITORY PERSPECTIVE AND THE PHYSICAL FACTORS AFFECTING IT, J. C. STEINBERG and W. B. SNOW, Bell Telephone Laboratories, Inc.

* ADAPTING THE SYSTEM TO THE CONCERT HALL, E. H. BEDELL, Bell Telephone Laboratories, Inc., and I. KERNEY, American Telephone & Telegraph Co.

* AMPLIFIERS, E. O. SCRIVEN, Bell Telephone Laboratories, Inc.

* THE TRANSMISSION ASPECTS, R. W. CHESTNUT and R. H. MILLS, Bell Telephone Laboratories, Inc., and H. A. AFFEL, American Telephone & Telegraph Co.

2:00 p.m.—Symposium on Electric Furnaces

THE THREE-PHASE ARC FURNACE AS AN INDUSTRIAL UNIT, SAMUEL ARNOLD, 3rd, Engineer and sales representative, Heroult Electric Furnaces.

ELECTRIC FURNACE TRANSFORMERS AND THEIR EQUIPMENT, H. O. STEPHENS and L. S. SCHELL, Jr., General Electric Co.

ELECTRODES—CARBON AND GRAPHITE, F. J. VOSBURGH, National Carbon Co., Inc.

ELECTRICAL EQUIPMENT FOR INDUCTION FURNACES, C. C. LEVY, Westinghouse Electric & Mfg. Co.

* THE ROCKING INDIRECT ARC ELECTRIC MELTING FURNACE, E. L. CROSBY, Detroit Electric Furnace Co.

* HIGH-FREQUENCY INDUCTION FURNACES, C. A. ADAMS, Harvard University, and J. C. HODGE and M. H. MACKUSICK, The Babcock and Wilcox Co.

Thursday, January 25

10:00 a.m.—Distribution

SUBURBAN DISTRIBUTION ECONOMICS AS DEVELOPED FOR THE BOSTON AREA, A. H. SWEETNAM and C. A. CORNEY, The Edison Electric Illuminating Company of Boston.

RADIAL VS. PRIMARY NETWORK DISTRIBUTION—COMPARATIVE COSTS FOR A CHICAGO AREA, H. E. WULFING, Commonwealth Edison Co.

FUNDAMENTALS OF ELECTRICAL DELIVERY SYSTEM DESIGN, J. ALLEN JOHNSON and R. T. HENRY, Buffalo, Niagara & Eastern Power Corp.

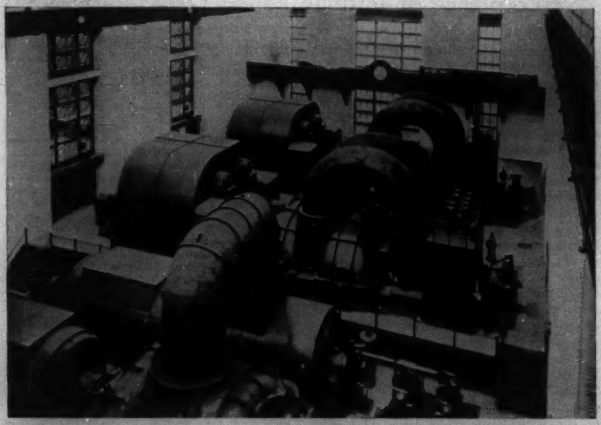
A COÖPERATIVE STUDY OF JOINT USE ON STATEN ISLAND INVOLVING 6,900-VOLT DISTRIBUTION, W. R. BULLARD, Electric Bond and Share Co., and D. H. KEYES, American Telephone & Telegraph Co.

10:00 a.m.—Electrical Machinery

EXPERIMENTAL IGNITION RECTIFIER, L. R. LUDWIG, F. A. MAXFIELD, and A. H. TOEPFER, Westinghouse Electric & Mfg. Co.

INDUCTION ALTERNATORS FOR THE GENERATION OF MODULATED HIGH FREQUENCY CURRENTS, F. W. MERRILL, General Electric Co.

INDUCTION MOTORS USED AS SELSYN DRIVES, L. M. NOWACKI, General Electric Co.



Hudson Avenue generating station of the Brooklyn Edison Company, Inc., Brooklyn, N. Y. This view of the turbine hall shows the 2 single-shaft 160,000-kw turbine-generator units each with one generator on the shaft, and in the foreground one of the 110,000-kw self-compound turbine-generators. This plant is one of the interesting points which may be visited by those attending the Institute's forthcoming winter convention to be held in New York, N. Y., Jan. 23–26, 1934. A description of the switching facilities at the Hudson Avenue station is given in this issue, p. 868–75

2:00 p.m.—Electrical Machinery

PROBLEMS INVOLVED IN DIRECT CONNECTING ROTATING MACHINES TO OVERHEAD LINES, J. F. CALVERT, Westinghouse Electric & Mfg. Co.

STEADY STATE CHARACTERISTICS OF SYNCHRONOUS MACHINES, S. B. CRARY, L. S. SHILDNECK and L. A. MARCH, General Electric Co.

SIMULTANEOUS CONTROL OF VOLTAGE AND POWER FACTOR, L. F. BLUME and F. L. WOODS, General Electric Co.

THE EFFECTS OF POLYPHASE RECTIFIERS ON A-C SUPPLY SYSTEM WAVE-SHAPE, P. W. BLYE, American Telephone & Telegraph Co., and H. E. KENT, Edison Electric Institute.

2:00 p.m.—Electrical Measurements

CROSS POTENTIALS OF A FOUR ARM NETWORK, A. C. SELETZKY, Case School of Applied Science.

PRODUCTION AND MEASUREMENT OF HEAVY SURGE CURRENTS, P. L. BELLASCHI, Westinghouse Electric & Mfg. Co.

A PORTABLE SCHERING BRIDGE FOR FIELD TESTS OF CONDENSER BUSHINGS, C. F. HILL, T. R. WATTS, and G. A. BURR, Westinghouse Electric & Mfg. Co.

* AN A-C POTENTIOMETER, S. L. BURGWIN, Westinghouse Electric & Mfg. Co.

IMPULSE GENERATOR CIRCUIT FORMULAS, J. L. THOMASON, General Electric Co.

* A NEW DEMAND METER, B. H. SMITH, Westinghouse Electric & Mfg. Co.

RULES ON PRESENTING AND DISCUSSING PAPERS

At some of the technical sessions papers will be presented only by title. This will permit the devotion of more time to discussion. At other sessions papers will be presented in abstract, 10 min being allowed for each paper unless otherwise arranged or the presiding officer meets with the authors preceding the session to arrange the order of presentation and allotment of time for papers and discussion. Authors will be notified officially in each case about one month in advance.

Any member is free to discuss any paper when the meeting is thrown open for general discussion. Usually 5 min are allowed to each discusser for the discussion of a single paper or of several papers on the same general subject. When a member signifies his desire to discuss several papers not dealing with the same general subject, he may be permitted to have a somewhat longer time.

It is preferable that a member who wishes to discuss a paper give his name in advance

* These papers are under consideration for presentation at the winter convention, but up to date of going to press have not been officially placed upon the program.

to the presiding officer of the session at which the paper is to be presented. Each discusser is to step to the front of the room and announce, so that all may hear, his name and professional affiliations. Three typewritten copies of discussion prepared in advance should be left with the presiding officer.

Other discussions to be considered for publication should be typewritten (in triplicate) and mailed to the A.I.E.E. editorial department, 33 West 39th Street, New York, N. Y.

Articles on X Rays Listed. The department of commerce of the U.S. Bureau of Standards, Washington, D. C., has prepared a list of publications of the Bureau of Standards on X rays and in addition included references to a number of other articles on X rays. The majority of papers and articles mentioned in this bibliography may be obtained from the government at a small cost. Copies of this bibliography which contains 41 references, may be obtained from the Bureau of Standards, Washington, D. C. It is designated as *LC*-389.

A Statement of Policy Governing Acceptance of Institute Papers From Nonmembers

THE question of whether the Institute should or should not accept for formal presentation and publication technical papers prepared by and bearing the signature of nonmembers of the Institute has been seriously considered by the Institute's technical program and other committees, as well as by its board of directors. Inasmuch as the Institute's policy with regard to nonmember authors has been tightened materially during the past year, and inasmuch as this policy is scheduled for rigorous enforcement toward the general exclusion of papers by non-member authors, a brief review and explanation of the whole situation is presented herewith in order that this important matter may be generally and clearly understood throughout the membership of the Institute.

Following a careful study of the matter, the board of directors at its meeting May 22, 1933, received the technical program committee's specific suggestions for revision of the by-laws to bring them into conformity with the policy proposed and, in accordance with established procedure in amending the by-laws, formally voted at its meeting June 28, 1933, to amend Sections 35, 45, and 91 of the by-laws to read as follows:

Sec. 35. District meetings shall be held, upon the approval of the board of directors in each instance, under the supervision of the geographical District officers and committees, in accordance with the following general plan:

Upon expression by a District executive committee of a desire to hold a District meeting, and approval by the board of directors, the responsibility for the meeting shall rest with a District meeting committee of 9, composed of the 7 members of the District coördinating committee and 2 additional members representing the Section in which the meeting is to be held. This committee shall have full responsibility and authority for organizing and conducting such meeting in all its details, including the arrangement of sessions, the entertainment features, and, subject to Section 91 of the by-laws, the selection of papers. Papers for a District meeting may be obtained from the District membership by the District meeting committee, and if papers are desired from outside the District they shall be obtained by coöperation with the national technical program committee. All papers included in the program shall be considered for publication upon the same basis as papers for national meetings. The financing of District meetings shall be in accordance with the consistent general plan approved from time to time by the board of directors, after consideration of such recommendations as may be received from the officers and committees concerned.

Sec. 45. Papers and discussions presented before a Section or Branch shall be the property of the Institute, and may be published only on authorization of the publication committee. Where publication in TRANSACTIONS of Section or Branch papers by nonmembers of the Institute is involved, approvals shall be obtained in accordance with Section 91 of the by-laws.

Sec. 91. All committees responsible for the preparation of technical programs shall so direct their activities that all authors of technical papers will be members of the Institute in so far as this is consistent with keeping the membership fully informed as to developments in the electrical arts and sciences and in closely allied fields. It is recognized that there may from time to time be situations in which non-member authors or co-authors are desirable in order to obtain an authoritative presentative of the subject matter, particularly in fields foreign but closely allied to the electrical arts and sciences. In such cases, papers by nonmembers may be accepted under regulations approved by the board of directors.

With particular reference to the revised Section 91, it is contemplated that when a District or technical committee chairman believes it desirable to have a non-member author or co-author for a technical paper proposed for formal publication by the Institute and presentation at a national or District meeting, he shall, before the paper is solicited or accepted for technical consideration, secure the approval of the chairman of the technical program committee and the national secretary. The national secretary will report to the board of directors the action taken in each case. Approval for non-member papers, when given, will constitute authorization for the proposer to solicit the paper or to receive it for consideration on the *same basis* as papers by member authors—for review and for approval or rejection on the basis of its intrinsic technical merits. It is earnestly desired that, when applying for approval of a non-member paper, the sponsor should state the special circumstances involved in the case, including the qualifications of the nonmember author and the reasons why approval is considered to be advantageous to the membership of the Institute.

Papers by nonmembers contemplated for Section or Branch meetings *do not* require any special approval by any authority other than the Section or Branch officers involved, except that the established procedure will prevail when such papers are submitted for consideration for possible formal publication by the Institute subsequent to or incident to their initial presentation.

OBJECTS TO BE OBTAINED

In developing these regulations it was generally agreed that the primary object of the Institute's technical publications and technical meeting programs is to keep the Institute membership informed as to contemporary developments in the electrical arts and sciences and also in closely allied fields. The desirability of meeting this objective by giving preference in so far as possible to papers prepared by Institute members is obvious, especially since a secondary object of the Institute publications is to provide a professionally acceptable channel through which members may make public a constructive record of their experiences and accomplishments.

It is fully recognized, however, that in some cases the achievement of keeping the membership informed as to contemporary developments may require special addresses and technical papers by authors who are not members of the Institute. Such papers, thoughtfully selected with reference to the character of proposed national or District meetings, may add distinctly to the interest and value of the meeting. In this connection, it is the expressed belief of many that have given the matter serious attention that non-member authors of papers preferably should be members in good standing of some recognized engineering or scientific body.

These restrictive regulations, of course, are directed at material formally designated as "A.I.E.E. technical papers" which, by recommendation of one or more of the technical reviewing committees, are made a part of the Institute's published record; none of the regulations is intended to limit or restrict the editorial policy of ELECTRICAL ENGINEERING as it relates to special articles of timely general interest, inasmuch as that policy was fully and carefully worked out by the publication committee and endorsed by the board of directors before it was placed in operation January 1, 1931.

A.S.T.M. to Have New Headquarters

The headquarters for the American Society for Testing Materials which for the past 14 years have been in the Philadelphia (Pa.) Engineers' Club Building, will be moved at the end of 1933 to the Atlantic Building, 260 South Broad Street (N. W. corner Broad and Spruce Streets), Philadelphia, Pa. This decision is the culmination of studies begun several years ago when it became evident that more adequate room in another location would be only a question of time and finances. The present quarters not only leave much to be desired in attractiveness and serviceability to members and visitors, but are also inadequate for the staff.

The new rooms comprise about 2,600 sq ft on the fifth floor of the Atlantic Building. This floor will be devoted to offices, reception room, members' lounge, and board room. Also, about 850 sq ft on the fourth floor will be used for storage of current and back publications, and as a shipping and general work room. The Atlantic Building, built in 1923, is among the finest in Philadelphia, and has a location convenient to railroad stations, hotels, and clubs.

Institute's 50th Anniversary to Be Observed Fittingly in May 1934

IN view of the fact that the 50th anniversary of the founding of the American Institute of Electrical Engineers occurs May 13, 1934, the Institute's board of directors at its meeting October 20, 1933, considered recommendations made by the publication committee and by the committee on coördination of Institute activities for a fitting observance of that anniversary. Accordingly, the board authorized and provided for the issuance of a special anniversary issue of ELECTRICAL ENGINEERING for May 1934, and authorized the president to appoint a special 50th anniversary committee to plan the celebration and to cooperate with the publication committee.

As chairman of the 50th anniversary committee President Whitehead appointed L. W. W. Morrow of New York, newly elected director of the Institute, and to serve with him, K. A. Auty of Chicago; A. W. Berresford, Gano Dunn, J. B. Jewett, and C. E. Stephens of New York; R. B. Bonney of Denver, Colo.; F. M. Craft of Atlanta, Ga., C. R. Higson of Salt Lake City, Utah; A. H. Hull of Toronto, Canada, B. D. Hull of Dallas, Texas; J. Allen Johnson of Buffalo, N. Y.; G. A. Kositzky of Cleveland, Ohio; E. B. Meyer of Newark, N. J.; C. E. Skinner of Wilkinsburg, Pa.; A. C. Stevens of Schenectady, N. Y.; R. W. Sorensen of Pasadena, Calif.; Stanley Stokes, St. Louis, Mo.; and A. M. Wilson of Cincinnati, Ohio. By request, President J. B. Whitehead of Baltimore, Md., also will serve as a member of the committee, which includes all vice-presidents of the Institute. Losing no time in getting at their task, this committee held a preliminary meeting at Institute headquarters in New York, November 22, 1933, the results of which will be reflected in later issues of ELECTRICAL ENGINEERING.

Anxious to omit no possible effort to produce a volume of ELECTRICAL ENGINEERING for May 1934 that will memorialize fittingly the Institute's half-century anniversary, the publication committee has forwarded the following letter to District, Section, and Branch officers of the Institute, and has provided for the reprinting of this letter in these columns so as to bring the matter directly to the attention of every member of the Institute, with an invitation for assistance and coöperation. Similarly, Chairman R. N. Conwell of the technical program committee has brought the matter to the attention of all chairmen of technical committees. Full text of the letter follows:

November 17, 1933

To all
Vice-Presidents and District Secretaries
Chairmen and Secretaries of Sections
Counselors of Student Branches

Fiftieth Anniversary
Gentlemen: A.I.E.E. May, 1934

As a part of the celebration of the Fiftieth Anniversary of the Institute, the Board of Directors has authorized a special issue of ELECTRICAL ENGINEERING. The Publication Committee and a Fiftieth Anniversary Committee, which has been appointed by the President, will supervise the preparation of this issue, for which the sum of $2,000 has been appropriated to defray extra publication expenses.

The issue will appear in May and will consist of about two hundred pages. There is a great deal of work to be done in a very short time and the appropriation is comparatively small.

Your coöperation is needed to make this anniversary issue a successful one, and suggestions regarding the type of material that will be of most value and the possible sources of such material are essential. Also, of major importance is the special advertising that might well be attracted to the issue if all possible channels are canvassed thoroughly. Since this issue should be of such value that it will be preserved by most of the membership as a reference volume its advertising appeal is obvious.

Tentative plans contemplate four general sections of the proposed issue as follows:

1—A section devoted to Institute history, reflecting also the lives and activities of the men responsible for the organization of the Institute and those prominent in its affairs.

2—A section of reprints, in whole or in part, of a few of the earlier A.I.E.E. technical papers that have proved to be of particular significance in the light of later developments.

3—A section containing a group of articles, each written by a past-president of the Institute, reflecting the human as well as the technological phases of electrical development.

4—A section containing one or two strong articles, especially inspiring articles, looking toward the future of the Institute and its professional relationship.

Will you please give the committee the benefit of your advice and any suggestions which you may have which will aid us in making this Fiftieth Anniversary Issue of ELECTRICAL ENGINEERING a particularly interesting one?

Very truly yours,
(*signed*) B. B. MEYER, *Chairman*
Publication Committee

Bibliography on Vibration in Electrical Conductors

A bibliography on conductor vibration containing a total of 176 items and prepared by the subcommittee on steel transmission towers and conductors of the Institute's power transmission and distribution committee was announced in the February 1932 issue of ELECTRICAL ENGINEERING, p. 135, as being available. This bibliography has now been extended to include all supplements and additions to November 1933, and contains some 165 mimeographed sheets bound in a single volume.

The general sections into which the bibliography has been divided are as follows:

1. Vibration of relatively small amplitude in electrical cables exposed to light winds, to excessive corona, and to other like media and phenomena.
2. Jumping, shaking, or dancing conductors due to a number of causes, one of which is partial glaze coatings and ice formations on the wires.
3. Wind structure.
4. Wind force, wind stresses, and wind bracing of buildings.
5. Wire rope research.
6. Sound and noise.
7. Fatigue and allied researches.
8. Inelastic behavior of springs and elastic hysteresis.

As long as they are available, copies of this bibliography may be obtained by members of the Institute particularly interested in the subject, from the following:

C. S. Rich, A.I.E.E. Headquarters, 33 West 39th Street, New York, N. Y.
D. M. Simmons, General Cable Corp., 420 Lexington Avenue, New York, N. Y.
A. E. Davison, Hydro-Electric Power Commission of Toronto, 620 University Avenue, Toronto, 2, Canada.

Future AIEE Meetings

Winter convention,
New York, N. Y., Jan. 23–26, 1934

North Eastern District meeting,
Worcester, Mass., Spring 1934

Summer convention,
Hot Springs, Va., June 25–29, 1934

Pacific Coast convention,
Salt Lake City, Utah, Sept., 1934

John Fritz Medal for 1934 Awarded

The John Fritz Gold Medal for 1934 was awarded to John Ripley Freeman at the regular annual meeting of the John Fritz Medal board of award, October 20, 1933. The award was made posthumously because of Doctor Freeman's sudden death on October 6, 1932, during the procedure for his selection as a medalist. The award was made by a board of 16 representatives of the national societies of civil, mining, mechanical, and electrical engineers, each representative being a past-president of one of these societies. The medal was awarded to Doctor Freeman as "Engineer—preeminent in the fields of hydraulics and water supply, fire insurance economics, and analysis of earthquake effects."

The John Fritz Gold Medal is awarded not oftener than once a year for notable scientific or industrial achievement without restriction on account of nationality or sex. It is a memorial to the late John Fritz, a leader in the American iron and steel industry, the first medal having been awarded to Mr. Fritz in 1902. Members of the Institute who have received this medal include: Elihu Thomson (A'84, F'13, HM'28, member for life, and past-president); Guglielmo Marconi (HM'17); Ambrose Swasey (HM '28); Edward D. Adams (A'10); Elmer A. Sperry (M'29); Herbert Hoover (HM'29); and M. I. Pupin (A'90, F'15, HM'28, member for life, and past-president). Other John Fritz medalists, no longer living, include: George Westinghouse (A'02); Alexander Graham Bell (A'84, M'84, and past-president); Thomas A. Edison (A'84, M'84, HM'28); and John J. Carty (A'90, F'13, HM'28, member for life, and past-president).

Doctor Freeman, the 30th engineer to receive the John Fritz Medal, was born at West Bridgeton, Maine, in 1855, and graduated from Massachusetts Institute of Technology in 1876. In this country, he has received the honorary degree of doctor of science from Brown University, 1904, Tufts College 1905, University of Pennsylvania 1927, and Yale University in 1931. His early years were spent in hydraulic power work in New England. In 1886 he became connected with the Associated Factory Mutual Fire Insurance Companies, at

Providence, R. I., and made outstanding contributions to improvement of mill buildings and development of fire prevention apparatus. In 1896 he became president and treasurer of a group of fire insurance companies, with offices at Providence. He was at various times member of boards for the study of water supply for Boston, Mass., and New York, N. Y., and was a member of a commission to study special problems of the Panama Canal relating to dam and lock foundations, prevention of earth slides, etc. His consulting engagements included many of the large communities of the United States and other countries, as well as many important industrial corporations. He inspired and led notable investigations of earthquakes. Doctor Freeman was president of The American Society of Mechanical Engineers in 1905, and of the American Society of Civil Engineers in 1922. In 1923 The American Society of Mechanical Engineers awarded him its gold medal "for eminent services rendered to industry and fire prevention." He was a member of United Engineering Trustees, Inc., and was also a member of the National Academy of Sciences and numerous other scientific and engineering organizations.

Engineers' Council for Professional Development Discussed

INTEREST at the meeting of the Middle Atlantic States Section of the Society for the Promotion of Engineering Education held at Cooper Union in New York, N. Y., November 11, 1933, centered on the Engineers' Council for Professional Development, which, as announced in the last 2 issues of ELECTRICAL ENGINEERING, is now being actively brought before the engineers of the United States.

Fifteen institutions in New York, New Jersey, Pennsylvania, and Delaware were represented at this meeting. Representatives of education and industry addressed the meeting, and plans were discussed to further what was described as "the most constructive and forward looking program that has ever been presented for advancing the status and recognition of the engineering profession." Among those who spoke at this meeting were: Dr. C. F. Hirshfeld (A'05) chairman of the Engineers' Council for Professional Development and chief of the research department of the Detroit (Mich.) Edison Company; Dr. D. B. Steinman, member of the executive committee of the E.C.P.D., and consulting engineer, New York, N. Y.; Prof. H. P. Hammond, member of the committee on engineering schools of the E.C.P.D., and professor of civil engineering at the Polytechnic Institute of Brooklyn, N. Y.; and Gen. R. I. Rees, chairman of the committee on professional training of the E.C.P.D., and assistant vice-president of the American Telephone and Telegraph Company, New York, N. Y. A. R. Cullimore, president of the Newark (N. J.) College of Engineering, presided, and R. Fulton Cutting, president of the board of trustees of Cooper Union, delivered an address of welcome.

Parts of the principal addresses delivered at this meeting are given in this article. Excerpts from Doctor Hirshfeld's address are as follows:

"We are living in a period in which it has become the style to question with the utmost freedom practically everything having to do with the life of man. Religious forms and teachings, social organizations and values, economic theories and practices, the significance of family life and family ties, physical science which was thought by many to rest on an absolutely unassailable foundation, all these and more are being subjected to an inquisition of unprecedented character and extent.

"It is commonly held that out of this chaos there is to emerge a new social, economic, and cultural order resulting from a revaluation of that which has been and a reorientation with respect to that which is to be. I find myself unable to travel with the mob in these respects. To me we shall end by discovering once more the reality and significance of certain eternal verities, or at least verities which shall be such for so long a time that for our present purposes we may regard them as eternal.

"History does not show any case in which an existing order, an existing culture, or an existing anything else of significance has been thrown away overnight and successfully replaced by new somethings created full grown from the brain of man. And I do not believe that we have suddenly become such superhuman individuals that we can accomplish successfully such a superhuman task.

"I feel very certain that we shall shortly realize that man is man, that in spite of a large admixture of idealism in the mass he is actuated very largely by considerations of self-interest as an individual. Moreover, I believe that we shall also realize that no workable social organization can be produced which does not take this into account and therefore provide for the rather generous exercise of the individualistic urge. And further, I am positive that we shall rediscover the impracticability of attempting to repeal by fiat, laws of economics and of human relations which, after all, are but expressions of the natural psychological reactions of man to certain conditions.

"If the industrialist insists on producing more shoes or more automobiles or more anything else than the market requires no governmentally hatched and administered plan is going to make the world pay more than the product is worth to it.

"You may wonder why I preface my address on the Engineers' Council for Professional Development with thoughts of this character. I have 2 reasons and both seem good to me.

"First, if we are to have any such tremendous social and economic upheaval as is being freely predicted and if out of it are to come such new forms of social and economic practice as has been freely predicted it would be foolish to carry on at the present time any such movement as this Council stands for. We might better wait to discover the characteristics of the new order and then attempt to determine what might be done to the best advantage under such conditions.

"Second, if we are, as I suspect, to return in the end to essentially what we had before, the sooner we can get a large part of the educated and potentially powerful and influential fraction of our population thinking sane thoughts based upon an appreciation of human nature and of human relations as they have shown themselves historically to be and undoubtedly still are, the better. It is practically the function of the Council to produce just such a result with respect to some part of that fraction.

"When all the political fireworks and minority smoke screens and theorists' 'Isms' have cleared away we shall find ourselves in much the same sort of a world as we grew accustomed to before we learned enmass to spend more than we had or could get and before we grew accustomed to believing that politically actuated congressmen and cloistered bureaucrats could solve problems and administer activities which tax the best brains that we have.

"Looking back over the world that has been, I think it very evident that the individual who we call the engineer has been always present, first in more or less embryonic form and later in what may be called the stages of childhood and of adolescence. To me he is just about emerging from the state of adolescence at present.

"Let me point out to you that he has only recently discovered the tremendous powers that he possesses and that, in characteristic adolescent fashion he has used them without any great amount of thought to the ultimate results of such use. Through his productivity he has radically changed the life of the human family. Very little is now done in the way in which it was done only a short time ago as time is reckoned in terms of human history.

"And now this virile but reckless youth appears to me to have arrived at the place where he must become grown up; where he must recognize his responsibilities to the other parts of the human family; where he must study well the probable effects of his seeds before he plants them and accept some measure of responsibility for his offspring, their doings, and their influence.

"You can see many signs of this if you will but look. The public press which is always a good reflector though often a poor evaluator is fairly consistent in blaming many of our present ills upon the engineer. All appear to agree that he has wrought well but irresponsibly. The States have in many cases decided that his works are of such tremendous significance and fraught with such potentialities for evil as well as for good, that it is necessary to use their police power to put some measure of control upon his activities.

"The industrialists and others who hire and who use engineers in large numbers are complaining that he is too single tracked an individual, that, in general, he knows one thing well and most others not at all.

You educators of engineers have become cognizant of the fact that the product of yesterday does not measure up to the demands of today and are working diligently and sometimes frantically to discover how to produce the product that seems to be demanded.

"As I see it the engineer has had a comparatively easy time of it. He has dealt with problems amenable to factual attack. To be sure, judgment has been required frequently in large measure but even then it had a fairly substantial factual basis. Working in this way he has advanced our civilization lopsidedly in that he outstripped the workers in other fields in which factual methods of attack have not been developed or possibly in some of which they are not applicable.

"There is nothing really alarming in this. Human progress has always been by means of wedges driven ahead of the general line of progress. The danger comes in permitting any wedge to get too far out ahead of the line. And, curiously, the human social organism seems to have an inherent reaction which prevents such catastrophies. The wedge is either lopped off or the line catches up. In the present case I am satisfied that we shall discover that we cannot get along without the engineer and his advances, therefore the wedge cannot be lopped off. We shall have to maneuver so that the line catches up."

In his address, Dr. D. B. Steinman described the immediate program of the Council. Excerpts from his address follow:

"To give the engineer a clearly recognizable professional standing, to make engineering an integrated, unified profession, and that new men shall enter with a consciousness of the profession as a defined, corporate entity, a coördinated system of selection, guidance, training, and certification must be developed, covering the entire period of preparation, education, and apprenticeship, from high school to admission into the profession.

"The general public cannot be expected to have proper appreciation of the true engineer until there is a clear cut line of recognition and certification instead of the present indefiniteness, misunderstanding, and confusion.

"This line of demarcation must clearly and recognizably separate the real engineer from the pseudo-engineer or the incompetent, the man admitted into the profession from the student engineer or engineer apprentice, the man with proper technical and cultural education from the untrained or half-trained, the man legally permitted to practice engineering from the man legally debarred.

"The present situation is unquestionably one of ambiguity and confusion. There is no logical reason why different engineering schools should give widely varying degrees for the same standard of attainment or identical degrees for different standards of attainment. There is no logical reason why different national engineering societies should have such diverse admission standards for membership, and such discrepant designations for membership grades of comparable standards. There is no logical reason why the different states should have differing qualification standards for the licensing of engineers.

"It is illogical for engineering societies to give their stamp of membership to men who the State Registration Boards cannot admit into the profession. It is illogical for the engineering schools to stamp young men as engineers by giving them the professional degree, when the profession holds and the law declares that these young men are not yet engineers and must undergo additional training through apprenticeship before they can use the professional degree. The strength and prestige secured by other professions in this country and the engineering profession in other countries are also attainable by us if we adopt a program of united action for these objectives."

Prof. H. P. Hammond discussed "The Problem of Accrediting Engineering Colleges," including in his address the following:

"Whatever our views as to the desirability of accrediting may be, we must recognize it as a condition to be dealt with and not merely as a theory. Accrediting of engineering colleges we already have with us, whether we approve of it or not. Engineering colleges are not only now recognized or approved by educational agencies—the several regional associations, associations of universities and colleges, and the like—but they are also recognized or approved by the profession through the national engineering societies and for legal purposes in many states by the state engineering licensing boards.

"Our present problem, therefore, is not to determine whether there shall be accrediting, but whether the schools themselves, either individually or through this Society as their common agency, or through its membership, in turn, in some other representative agency, shall participate in determining the methods and procedures and the standards in accordance with which they shall be accredited."

Announcement of A.I.E.E. Prizes for Technical Papers

AUTHORS who plan to present papers before the Institute during the calendar year 1934, those who have presented papers during 1933, and others who may wish to submit papers for prizes, would do well to bear in mind that such papers are eligible for consideration for Institute prizes. These awards are made each spring for the preceding calendar year, and fall into 2 main classes, national and District prizes.

On account of the reduced income of the Institute, the board of directors decided to omit the cash awards for papers presented during the calendar year 1933, except that a payment of $25 in cash will accompany each District Prize for Branch Paper. All certificates will be issued as usual, those for national prizes signed by Institute officers, and those for District prizes signed by the officers of the Districts concerned. In cases of joint authorship, a certificate will be issued to each author.

National Prizes

The national prizes which may be awarded at the discretion of the committee on award of Institute prizes are as follows:

1. Prizes for best papers in (1) *engineering practice*, (2) *theory and research*, and (3) *public relations and education*.
2. Prize for initial paper.
3. Prize for Branch paper.

The national prize for best paper in each of the 3 classes indicated may be awarded to the author or authors of the best original paper presented at any national, District, or Section meeting of the Institute, provided the author, or at least one of co-authors, is a member of the Institute.

The national prize for initial paper may be awarded to the author or authors of the most worthy paper presented at any national, District, Section, or Branch meeting of the Institute, provided the author or authors have never previously presented a paper which has been accepted by the technical program committee, and the author, or at least one of co-authors, is a member of the Institute or is a graduate student enrolled as a Student of the Institute.

The national prize for Branch paper may be awarded to the author or authors of the best paper based upon undergraduate work presented at a Branch or other Student meeting of the Institute, provided the author or authors are Student Branch members.

All papers approved by the technical program committee which are presented at any meeting will be considered by the committee on award for the prizes for best paper and initial paper without being formally offered for competition. All papers other than those presented to the technical program committee must, in order to receive consideration, be submitted in triplicate with a written communication to the national secretary on or before February 15 of the year following the calendar year in which they were presented. This may be done by the author or authors, by an officer of the Institute, or by the executive committees of Sections, or Geographical Districts.

District Prizes

The following District prizes may be awarded each year in each Geographical District of the Institute.

1. Prize for best paper.
2. Prize for initial paper.
3. Prize for Branch paper.

A District prize may be awarded only to an author who, or to co-authors of whom at least one, is located within the District, and for a paper presented at a meeting held within, or under the auspices of, the District.

The District prize for best paper may be

awarded for the best paper presented at a national, District, or Section meeting, provided the author, or at least one of co-authors, is a member of the Institute.

The District prize for initial paper may be awarded for the best paper presented at a national, District, Section, or Branch meeting, provided the author or authors have never before presented a paper before a national, District, or Section meeting of the Institute, and the author, or at least one of co-authors, is a member of the Institute or a Graduate student enrolled as a Student of the Institute.

The District prize for Branch paper may be awarded for the best paper based upon undergraduate work presented at a Branch or other Student meeting of the Institute, the author or authors of which are Student Branch members.

All papers to be considered in competition for District prizes must be submitted in duplicate by the authors or by the officers of the Branch, Section, or District concerned to the District committee on awards on or before January 10 of the year following the calendar year in which the papers have been presented.

Copies of a pamphlet entitled "National and District Prizes" may be secured, without charge, upon application to Institute headquarters.

Much Unemployment Relief Carried On During Past Year

UNEMPLOYMENT relief being carried on in the metropolitan area of New York, N. Y., by the Professional Engineers Committee on Unemployment, known locally as the P.E.C.U., is worthy of national attention as it affords a guide to similar work which has been and may be carried on in other sections of the country. A summary of this work for the year ending October 1, 1933, therefore is presented herewith, similar to that for the previous year given in ELECTRICAL ENGINEERING for November 1932, p. 809–13. At the end of the present report, a proposed plan for extending employment of engineers is given.

The P.E.C.U. represents the New York Sections of the American Society of Civil Engineers, The American Society of Mechanical Engineers, the American Institute of Electrical Engineers, the American Institute of Mining and Metallurgical Engineers, and the Society of Naval Architects and Marine Engineers.

As contact could not be kept with all individuals who had registered with the P.E.C.U. during the year 1931–32 without heavy expense, a completely new registration was opened in October 1932; 3,015 were registered this year, of which 957 also were registered during the previous year. Of this total 50 per cent were financially able to take care of themselves and consequently the principal effort was devoted toward the relief of those who were either destitute or close to destitution. Relief had been guided by the degree of destitution rather than by society membership, provided investigation of the applicant's past record showed that he was truly within the engineering profession. In Tables I and II, information on registration and placement is summarized, and in Tables III, IV, and V, is given information on the registrants prior to their being enrolled with the P.E.C.U. In Table VI, the estimated dollar values in earnings made by the registrants placed by this organization during the past year, and the sources from which the funds were supplied are given.

The P.E.C.U. coöperated with the Engineering Societies Employment Service in the placing of members in engineering positions, but left the placement in these positions largely to this employment service. Since many men have been placed through this latter organization who were not on the rolls of the P.E.C.U., the accompanying tables should not be construed to be a true indication of engineering reëmployment. Engineering positions have been found for 6 per cent of the total registrants of the P.E.C.U., made work for 19 per cent, and non-engineering positions for 8 per cent. In addition 7.5 per cent have received loans totaling $8,239.50; 31.5 per cent have received food, clothing, shelter, medical aid, or other relief through the social service subcommittee, and the women's committee alone has aided 194, or about 6 per cent of the registration.

A series of educational courses directed by Dr. A. D. Flinn, secretary of the United Engineering Trustees, Inc., were attended by over 200 engineers, and Columbia University opened its doors without cost to 138 engineers certified by the P.E.C.U. This work has done much to maintain the morale of those not having regular positions.

FINANCIAL STATEMENT

During the past year the P.E.C.U. has received contributions in cash of $52,961.91, making a total contributed during the 2 years of operation $160,369.87. A balance of $20,242.63 was left by the previous committeee to begin this year's activities; $57,264.52 has been expended, leaving a balance of $15,798.35 to begin the coming year. All of this money has gone as direct relief to unemployed engineers. The staff is composed of destitute engineers receiving $5 per day as salary, and a few volunteers are serving without pay. Stenographic assistance was furnished by the city relief bureau. General expense such as printing, postage, and telegrams, amounting to $5,484.27, has been furnished by the local sections of the engineering societies and by special donations for this purpose. Space in the Engineering Societies Building has been provided for staff offices. The financial statement as of September 30, 1933, is given in Table VII.

Table II—Actual Positions Filled

P.E.C.U. staff and field	92
Engineering positions	180
Emergency work bureaus	477
Other non-engineering positions	240
Total	989

Table III—Ages of Registrants

Under 30 years of age	1,018
From 31 to 40	1,129
From 41 to 50	619
Over 51	249
Total	3,015

Table IV—Analysis by Salary Groups

Previous Salary	
Over $6,000 per year	168
From $3,600 to $6,000 per year	701
From $2,400 to $3,600 per year	1,323
Less than $2,400 per year	823
Total	3,015

Table I—Classification by Societies

	Registered	% of Total Registration	Placed	% of Total Placed	% of Each Society Placed
Am. Soc. Mec. Engrs.	516	17.1	186	22.7	36.0
Am. Soc. Civil Engrs.	340	11.3	118	14.4	35.2
Am. Inst. Elec. Engrs.	259	8.6	82	10.0	31.7
Am. Inst. Min. & Met. Engrs.	49	1.6	20	2.4	40.8
Soc. Naval Arch't and Marine Engrs.	10	.3	4	.5	40.0
Former society members	112	3.7	27	3.3	24.1
Nonmembers	1,729	57.4	383	46.7	22.2
Total	3,015	100.0	820	100.0	27.2

WORK OF THE SOCIAL SERVICE DIVISION

The services now rendered by the social service committee of the P.E.C.U. started on November 30, 1932 and include the following: food; clothing, emergency cash loans, medical aid and hospitalization; lodging relief; home mortgage foreclosure prevention; dispossess preventing and rent relief; gas and electric shut-off prevention; fuel supply; legal aid; advisory assistance to raise money on frozen assets, and visits to the home by the Women's committee social worker. Out of the 3,800 registrants of P.E.C.U., 900 have come to the social service division for help. A little more than

Table V—Analysis by Previous Positions

Previous Position	Registrants
Draftsmen	
Structural	628
Industrial	566
Construction	
Superintendence	213
Surveyors	215
Office workers	285
Industrial	
Plant engineers	352
Office workers	27
Sales engineers	113
Recent graduates	121
Mining engineers	17
Chemical engineers	11
Research engineers	85
Marine engineers	30
Radio engineers	54
Geologists	8
Public utilities engineers	159
Valuation and appraisal engineers	23
Miscellaneous	108
Total	3,015

Table VI—Estimated Dollar Value of Earnings During Past Year

Professional Engineers Committee on Unemployment	$44,276.00
Emergency work bureaus	192,168.00
Engineering positions	103,151.00
Other nonengineering positions	144,482.00
Men placed during the 1931–32 season who are still employed and registered with P.E.C.U.	254,574.00
Total estimated earnings of registrants	$738,651.00

one-half of this number are not members of any one of the principal engineering societies; about 45 per cent are members.

During the 10 months' activity of this committee prior to October 1, 1933, groceries and food in 30-lb packages aggregating over 108,000 lb have been supplied through the coöperation of the American Red Cross and the city's work bureau. Also more than 7,400 emergency meal coupons have been given to single men. Donations of new and used clothing and of shoes, have been received and widely distributed, and a special children's shoe fund has been set up. These and the other items mentioned above have been of considerable assistance to the registrants of the P.E.C.U. and their wives and children.

Activities of Women's Committee

A women's division of the P.E.C.U. was formed January 2, 1933, to handle special cases referred to it. A total of 365 cases was submitted to this committee during the first 9 months of its operations and in 184 cases aid has been given. The majority of the other cases were turned over to the employment department since the special need in these latter cases was work.

In addition to supplying shoes, clothing, fuel, emergency loans, and similar aid, one of the most important phases of the work of this committee has been in furnishing medical aid, 96 medical cases having been cared for. It has been found that in many cases the extending of sympathy was greatly appreciated, sometimes valued at even more than financial aid, and has assisted in maintaining morale.

Proposed Plan for Extending Employment

During the past year the P.E.C.U. has interviewed practically every firm in the New York area in which there is a member of the A.S.M.E. or the A.I.E.E. Banks, title companies, and similar organizations also have been contacted, and since the inauguration of the National Recovery Act contact with as many as possible of all large companies has been maintained. Approximately 3,000 contacts made during the past year have resulted in 535 temporary opportunities and 345 permanent opportunities. It has been found that in many cases requests have come in for men a number of weeks after these calls were first made.

Experience obtained by the P.E.C.U. indicates that such activity, although valuable, is not adequate to take care of the present situation, and that engineering opportunities must be discovered in industries not now using engineers to a great extent. It is proposed to study each industry to discover unrecognized openings for the engineer. These openings must:

1. Be positions bringing an attractive financial return to the employer.
2. Be positions which only the engineer can fill.
3. Not interfere, for the present at least, with anyone now employed.

There are 2 major obstacles in the discovery of such openings:

1. The employer must be convinced of his need by showing him the large losses which he is now experiencing through lack of engineering assistance.
2. The unemployed engineer is discouraged by continuous and unsuccessful job-hunting, and only a few understand the technique of job-finding.

The proposed plan is as follows:

1. Select one engineer from each industry or phase of engineering activity, to organize a committee within the industry or phase of activity.
2. This committee to study the industry to discover opportunities for engineering usefulness.
3. List these opportunities and specify the qualifications of the engineer to fill these positions.
4. Send this list and specification to the P.E.C.U.
5. Prepare written arguments to employers showing the advantages of employing engineers for such positions.

The P.E.C.U. will then notify properly qualified engineers that such opportunities are available in this industry and advise the engineer to:

1. Study the industry.
2. Study himself.
3. Prepare a written statement of the service he can render the proposed employer.
4. With the assistance of the P.E.C.U. the employing individuals in the industry will be found for the engineer but he must secure the position through his own efforts in presenting logical reasons for such employment.

In the meantime, the P.E.C.U. will have circularized the prospective employers in an effort to convince them of the need of employing engineers. They will further help the engineer by advice and in studying the industry but will insist that each man secure his place by his own efforts.

No attempt will be made to organize all industries at one time. Only as rapidly as suitable personnel for the committees has been secured, will the studies be started. Further, no attempt will be made to extend this work nation-wide until at least one industry is organized. This work must be done thoroughly, bearing in mind that a few mistakes in placing unqualified engineers in new activities will do untold harm. However, the local sections of the national engineering societies will be kept informed of progress.

Table VII—Financial Statement of Relief, Sept. 30, 1933

Receipts			
Balance on hand Oct. 1, 1932		$20,242.63	
Cash received Oct. 1 to Aug. 31, 1933		51,961.91	
Repaid loans, September		10.00	
Old contributions, September			
New contributions, September		911.33	
Total		$73,125.87	
Undeposited receipts		63.00	
		$73,062.87	
Pledges unpaid		578.10	
Grand total			$73,640.97
Expenditures			
Relief payments Oct. 1 to Sept. 30, 1933		$44,736.00	
Loans (gross)		8,184.50	
Relief committee total	$52,920.50	(a)	
Social service committee	2,850.00		
Board of transportation fund	415.00		
Courses for disengaged engineers	480.00		
U. S. coast and geodetic survey	599.02		57,264.52
Balance available Sept. 30			$16,376.45
Less pledges unpaid			578.10
Total cash in banks Sept. 30			$15,798.35

(a) Appropriation to August 14, 1933—$58,000

Many Foot-Candle Meters Sold. Attention has been called by G. H. Stickney (A'04, F'24) consulting engineer of the General Electric Company, Cleveland, Ohio, to the fact that an aggregate of over 9,000 foot-candle meters has been made and sold in the United States. The foot-candle meter is an instrument used to measure values of illumination, especially throughout the ranges of artificial lighting as employed indoors.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

A Special Slide Rule for Calculating $\sqrt{a^2 + b^2}$

To the Editor:

For the benefit of those interested in "A Short Cut to Finding $\sqrt{a^2 + b^2}$" discussed in "Letters to the Editor" in the last few issues of ELECTRICAL ENGINEERING, I wish to say that the shortest method for computing such quantities is by means of the log log vector slide rule. This rule is described in full in a paper "Vector Calculating Devices" presented by the author at the seventh regional meeting of the A.I.E.E., March 7–9, 1928, and is now manufactured by the Keuffel & Esser Co.

For its determination by means of this vector slide rule the radical $\sqrt{a^2 + b^2}$ is thought of as the hypothenuse of a right triangle whose 2 other sides are a and b. Only 2 movements of the hair line are necessary to obtain the value of the radical and of its angle with either of the triangle sides a or b, if the radical is actually a coplanar vector quantity.

The trigonometric scales on this rule are decimally subdivided and folded 3 times so that the 10-in. rule is equivalent to a rule 30 in. long. As a consequence the calculations are sufficiently accurate for all practical purposes.

This rule is also designed for the rapid determination of the component values a and b when the radical $\sqrt{a^2 + b^2}$ is a coplanar vector and its angle with either a or with b is known, as is necessary in numerous calculations pertaining to alternating current circuits.

It may also be of interest that this vector rule has in addition to the usual scales found on duplex rules and the trigonometric scales mentioned above, folded scales of the hyperbolic functions sinh x and tanh x. These scales in conjunction with the trigonometric scales are designed for the rapid determination of the hyperbolic sine, cosine, and tangent of complex functions $x + jy$, which enter into the calculations of electric filters, transmission lines, and numerous other types of circuits.

Very truly yours,

M. P. WEINBACH (A'22, M'31)
(Professor of Electrical Engineering, The University of Missouri, Columbia, Mo.)

A Short Cut to Finding $\sqrt{a^2 + b^2}$

To the Editor:

Considerable space, in past issues of ELECTRICAL ENGINEERING has been devoted to showing methods and short cuts for obtaining a solution of this form. F. V. Andreae, in the October issue, p. 724, indicates a practical method but does not mention its limits.

The writer has used a method similar to the one outlined but which could be modified to suit conditions.

It is obvious that $\frac{a}{b} = \tan \alpha$; calling $\sqrt{a^2 + b^2} = c$, then $c = \frac{a}{\sin \alpha}$ and $c = \frac{b}{\cos \alpha}$. It is a simple matter, knowing $\tan \alpha$, to obtain either $\sin \alpha$ or $\cos \alpha$ from a table of trigonometric functions, notably "The Engineers' Manual," by R. G. Hudson and associates, in which the sine, cosine, and tangent functions are side by side. Whether the sine or cosine function should be used will depend upon the relation a/b. If the angle is less than 10 deg the sine value will give best results; and a minimum change of setting might be required; for angles close to 90 deg the cosine values will give best results.

Also, there is available a slide rule by means of which the desired calculation can be made directly without tables.

Very truly yours,

C. O. VON DANNENBERG (M'30)
(297 Lincoln Place, Brooklyn, N. Y.)

A New Method of Calculating Circuits

To the Editor:

While it is perhaps dressed in a new cloak the method of calculating circuits described by W. B. Kouwenhoven and M. W. Pullen in ELECTRICAL ENGINEERING for November 1933, p. 776–9 is not at all new. What they are really doing is applying the well-known formula for the equivalent electromotive force of a group of alternators in parallel;

$$E = \frac{\Sigma y_s E_s}{\Sigma y_s} \qquad (1)$$

If one of the circuits is a load it is included as an alternator of zero electromotive force. The current from the s^{th} alternator is

$$I_s = y_s(E_s - E) \qquad (2)$$

and the current through the load (a particular case with $E_s = 0$)

$$I_L = -y_L E \qquad (3)$$

Calling the $y_s E_s$ group the short-circuit currents and putting the impedance $1/\Sigma y_s = Z_s$ does not make the method new.

This method of calculating has been taught here for many years as an exercise on Thevenin's Theorem. Pollard's shunted cell is a particular case.

The authors might have sensed the true position of their work in network analysis if they had used the admittance notation more freely. To use impedances entirely in what is clearly a parallel circuit problem is an unfortunate restriction upon one's mental processes.

Very truly yours,

V. G. SMITH (A'26)
(Assistant Professor of Electrical Engineering, University of Toronto, Toronto, Ontario, Can.)

Engineering Schools and the Changed Conditions

To the Editor:

Professor Karapetoff's article "Engineering Schools and the Changed Conditions" in ELECTRICAL ENGINEERING for September 1933, p. 604–5, warrants discussion by other engineering teachers. I shall mention briefly what we in the Moore School have already done in connection with some of the problems considered by Professor Karapetoff and then comment on one important aspect of engineering education.

In 1925, 8 years prior to Professor Karapetoff's article, 2 of the younger members of the staff of the Moore School discussed with Dean Pender the possibility of revising the curriculum along lines almost identically those recently suggested by Professor Karapetoff. Dean Pender, instead of acting as "an opposing force of inertia and resistance," not only listened sympathetically to these suggestions, but expressed himself as fully in accord with them. The result was that a new curriculum was prepared and put into effect in the fall of 1925. Eight years' experience with this curriculum, which has been modified only in minor details, justify us in endorsing whole heartedly the thesis propounded by Professor Karapetoff.

Application and design courses have been eliminated and the undergraduate curriculum is now composed entirely of intensive and rigorous courses in fundamentals. It is a "rigid curriculum" as far as engineering subjects go. On the other hand, students have great leeway in choosing non-engineering courses.

We feel that a man with a thorough fundamental training is in a position to *begin* the study of any specialty and make fairly rapid progress in it. He knows little "current practice" in any field, but we find that he acquires it very rapidly after graduation, and information thus obtained is much more up to date and pertinent than it would be possible to teach in school.

Another change in the Moore School, a change which was something of a novelty in 1925 although much less so now, is that all examinations are completely "open." The student has the privilege of consulting any reference he desires. Memory work has thus been almost en-

tirely eliminated. The system has proved eminently sucessful.

It will be seen that our attempt to meet the conditions outlined by Professor Karapetoff, in so far as they refer to curriculum, differs radically from that described for Harvard University by Professor Dawes in a "Letter to the Editor." (See ELECTRICAL ENGINEERING for September 1933, p. 647.) The latter disparages a "rigid curriculum," a thought with which we cannot agree. Time is not available to cover fundamentals completely, and it seems to be a logical contradiction to divert the student's attention to other topics before fundamentals have been covered. As for the idea that a rigid curriculum discourages outstanding students (it apparently does not in medical schools) the answer seems to be simple. In the Moore School courses are attuned to the pace of good students, not that of the average.

Turning to another problem, let us consider the length of the usual engineering course. Professor Dawes says, "It is realized generally that today the standard 4-year course is too short for the effective training of engineers." If this be true, then it is up to the engineering teachers to do something about it. It is doubtful that any one engineering school can increase its entrance requirements greatly without similar action by others. Many engineering schools now provide a 5 or 6 year combined college and engineering course, but the number of undergraduate (using the term in its broad sense as is done in medical schools) engineering students with college degrees remains small.

There seems to be a need for unity of action. Experience has shown that little is to be expected from the engineering societies. On the other hand, the Engineers' Council for Professional Development is now studying problems intimately connected with the problem here discussed. Two ideas occur: (1) Could not a group of leading engineering schools throughout the country act in unison in an attempt to set the pace for others, or (2) could not all the engineering schools in one section of the country do this?

I am reminded—it is unfortunate that this cannot be checked for exactness at the time of this writing—that in the article "Law" in "Recent Social Trends" (the report of the President's committee) it is pointed out that certain standards not even approximated at the time of adoption by any law school were met by all the better ones within 10 years. With evidence such as this, with medical schools requiring 3 years of college work before entrance, with standard 5-year courses in schools of architecture, and with the general realization of the need of more time for engineering studies which Professor Dawes mentions, it seems that the engineering schools are waiting for some person or organization to lead them on. We of the Moore School staff would be glad to coöperate with other engineering faculties in studying a method of achieving this end.

Very truly yours,

J. G. BRAINERD (A'32)
(Ass't Professor, Moore School of Electrical Engineering, University of Pennsylvania, Philadelphia)

Dissimilar Voltage and Current Waves at a Transition Point

To the Editor:

Conventional traveling wave theory assumes no distortion and a current wave which is an exact replica of its associated voltage wave. Actually, however, as a surge travels along a transmission line the current and voltage waves depart from similarity and may arrive at the transition point considerably different in shape. This note derives the appropriate transition point equations for such a contingency, and points out an interesting consequence. Let

e = incident voltage wave
i = incident current wave
e' = reflected voltage wave
i' = reflected current wave
e_0 = total voltage at transition point
i_0 = total current at transition point
Z = surge impedance of the transmission line
$Z_0(p)$ = generalized impedance at transition point

At the transition point the reflected current and voltage waves are related by the equation

$$e' = -Zi' \tag{1}$$

At points beyond the transition point e' and i' cease to be similar, but they are practically replicas during their development. The conditions of voltage and current continuity require that

$$e_0 = e + e' = Z_0(p) \cdot (i + i') = Z_0(p) \cdot \left(i - \frac{e}{Z}\right) \tag{2}$$

Therefore

$$e' = \frac{Z}{Z_0(p) + Z} [Z_0(p)i - e] \tag{3}$$

$$e_0 = \frac{Z_0(p)}{Z_0(p) + Z} (Zi + e) \tag{4}$$

If $Zi = e$ eqs 3 and 4 revert to the conventional ones. One obvious fact appears in eq 4; steep wave front effects will be dominated by the steeper of e and i, and sustained tail effects by the longer of e and i. As simplest possible example take

$$Z_0(p) = R$$
$$e = E(\epsilon^{-at} - \epsilon^{-bt})$$
$$i = I(\epsilon^{-mt} - \epsilon^{-nt})$$

Then

$$e_0 = \frac{R}{R + Z} [ZI(\epsilon^{-mt} - \epsilon^{-nt}) + E(\epsilon^{-at} - \epsilon^{-bt})]$$

Thus e_0 duplicates neither e nor i in shape but is a compromise between them, having the front of the steeper and the tail of the longer.

Now suppose that the terminal impedance is a capacitance, so that $Z_0(p) = 1/Cp$. Then eq 4 gives

$$e_0 = \alpha ZI \left[\frac{\epsilon^{-mt}}{\alpha - m} - \frac{\epsilon^{-nt}}{\alpha - n}\right] + \alpha E \left[\frac{\epsilon^{-at}}{\alpha - a} - \frac{\epsilon^{-bt}}{\alpha - b}\right] + \alpha\epsilon^{-\alpha t} \left[\frac{(n - m)ZI}{(\alpha - m)(\alpha - n)} + \frac{(b - a)E}{(\alpha - a)(\alpha - b)}\right]$$

If $ZI = E$, $m = a$, and $n = b$ this becomes

$$e_0 = 2\alpha E \left[\frac{\epsilon^{-at}}{\alpha - a} - \frac{\epsilon^{-bt}}{\alpha - b} + \frac{(b - a)\epsilon^{-\alpha t}}{(\alpha - a)(\alpha - b)}\right]$$

Thus current and voltage dissimilarity introduce twice as many terms in the transition point equations as would exist if the dissimilarity did not exist. Of course, in most practical cases the dissimilarity is not marked enough to cause much discrepancy, especially since the reflection tends to average out the difference.

Very truly yours,

L. V. BEWLEY (A'27)
(Power Transformer Dept., General Electric Co., Pittsfield, Mass.)

The Engineer of Forty

To the Editor:

He may be 40, or he may be anywhere between 35 and 45. He has had a successful career of 15 to 25 years; he is at the peak of his professional usefulness. Nevertheless, he is unemployed, through no fault of his. He is merely a victim of the depression; either his company has been liquidated, or he has been forced out due to extensive retrenchment.

He has applied for literally hundreds of positions, and has been turned down. Many prospective employers have not even shown him the courtesy of saying "No!"—they just left his inquiries unanswered.

What is this poor fellow to do?

Kind souls have advised him to try something new—something different from what he used to do before! But this engineer of 40 does not really altogether lack imagination; he has tried to find some new kind of occupation. However, his efforts along those lines have been thwarted.

Prospective employers, these days, seem to be very particular in their demands. They have very precise specifications as to kind of experience, length of service, age—and yes, the color of the eyes, the shape of the nose, and the length of the ears!

This poor chap has tried to land a job as factory superintendent, dish washer, college professor, janitor, chief engineer, laborer, teacher, gardener, watchman, and so on up and down the line. He has been steadily refused a niche—some say he is too good for the job, some say he has not had the experience required, some refuse to talk to him because he is past 38, or even 35. But no one asks him if he can do the job—apparently, there is no doubt on that score!

It is high time that prospective employers wake up to this economic loss, for economic loss it is!

This engineer of 40 is not a rare freak. There are thousands of his type. Their education represents a definite investment, their years of experience have cost some organization dollars and cents. Is this investment, this national asset, to be thrown to the 4 winds?

Then, there is the human aspect of the question. This man has stood the strain wonderfully well; he has kept up his

morale for months and even for years, but he cannot do this indefinitely. It is not humanly possible. What is more, the outlook is getting darker every day. Younger men getting jobs, with the N.R.A. and all, people are beginning to feel that if a man is unemployed, it must be his own fault. They are entirely too ready to overlook the vicious circle in which our engineer of 40 is laboring.

There was a certain amount of dead wood that had to be cleared away from industry. That has been done. What needs to be done now, is to reabsorb the really competent and deserving. We need less emphasis upon age and exact kind of experience, and more attention to each individual case to determine its merits fairly and squarely!

Ask this engineer of 40 what he can do, and give him the benefit of the doubt. You will find that he will not take advantage of you. If anything, he will be supercritical with himself, and underrate his own abilities, for, he is not a salesman!

Very truly yours,

A. F. HAMDI (M'21)
26 Roumfort Ave.,
Philadelphia, Pa.)

Standards

Mercury Arc Rectifiers

The sectional committee on mercury arc rectifiers has submitted a report on "Standards for Acceptance Tests of Metal Tank Mercury Arc Rectifiers." This sectional committee is under the sponsorship of the A.I.E.E. and the chairmanship of E. L. Moreland. The report was approved by the standards committee of the Institute on October 19, 1933, and later by the board of directors. It will now be transmitted to the American Standards Association for final approval as an American standard. On action to that effect the standards will become available in pamphlet form as one of the A.I.E.E. standards series.

Test Code for Synchronous Machines

There has been available since January 1933 a "Preliminary Report on a Proposed Test Code for Synchronous Machines." This report was prepared under the auspices of the A.I.E.E. committee on electrical machinery. It is the second in the proposed series of test codes, that on transformers having been issued in July 1931. The subcommittee having the code in hand is desirous of making at an early date a final report embodying suggested revisions and changes. Copies of the proposed code can be obtained from Institute headquarters without charge. Suggestions on changes or additions to the code should be sent to H. E. Farrer, secretary, standards committee, A.I.E.E., 33 West 39th St., New York, N. Y.

Standardization of Vacuum Tubes for Industrial Purposes

The Institute has accepted an invitation to appoint representatives on a proposed "Sectional Committee on Standardization of Vacuum Tubes for Industrial Purposes." This committee will work under the rules of procedure of A.S.A. and the sponsorship of the Electrical Standards Committee. The scope of work has been set up as follows: "Definitions, classification, methods of rating and testing, dimensions and interchangeability of vacuum tubes for power and industrial purposes." The Institute delegation will consist of J. H. Morecroft, *chairman*, Leo Behr, and a third member not yet selected.

Personal Items

L. F. HICKERNELL (A'25, M'27) has been appointed chief engineer of the Anaconda Wire and Cable Company, Hastings-on-Hudson, N. Y. Since joining this organization in 1931 he had served as electrical

L. F. HICKERNELL

engineer. He received the degree of bachelor of arts from Grinnell College in 1920, and that of bachelor of science in electrical engineering from Massachusetts Institute of Technology in 1922. While in college he was employed by the Iowa Light, Heat and Power Company, Grinnell, Iowa, in various capacities. Upon graduation from M.I.T. he joined the graduate student engineer course of the General Electric Company at Lynn, Mass. For a short period he was then instructor in electrical engineering at Iowa State College, resigning in 1923 to enter the engineering department of the Consumers Power Company, Jackson, Mich., as assistant investigations engineer in the electrical department. In this position he supervised electrical construction estimates and preliminary designs, system studies, special calculations, and technical and economical reports. He also was in charge of engineering committee work. In 1924, he became assistant investigations engineer of the successor company, the Commonwealth Power Corporation of Michigan. In 1927 he became general engineer in the electrical engineering department of the latter organization, acting in a consulting capacity, and engaged in studies of special problems, also continuing in charge of engineering committee work. In 1929 Stevens and Wood, Inc., succeeded this company, and in 1930 this concern was in turn succeeded by Allied Engineers, Inc.; Mr. Hickernell continued as general engineer with these organizations, until the disbandment of the latter organization in 1931. Becoming electrical engineer of the Anaconda Wire and Cable Company at that time he was placed in charge of its cable engineering department and the Hastings-on-Hudson laboratory. As chief engineer he will be in charge of the engineering department and all laboratories. He has served the Detroit-Ann Arbor Section of the A.I.E.E. in various capacities, having been chairman 1929–30; he also has served the Institute as member, executive committee of the Great Lakes District 1928–30; member, electrical machinery committee 1929–33; member, protective devices committee 1929–32, and vice-chairman during the last 2 of these years; and member of the power transmission and distribution committee since 1930. He has also served on many committees of the former National Electric Light Association, the American Society for Testing Materials, National Research Council, and the Insulated Power Cable Engineers Association. He has contributed numerous reports and papers before these organizations.

P. H. PATTON

P. H. PATTON (A'18, M'25) telephone engineer, Northwestern Bell Telephone Company, Omaha, Neb., retired from active service November 1, 1933. Mr. Patton had completed 40 years of service with the Bell telephone system. In 1891 he engaged in telephone work in Denver, Colo., as installer and test man, and for the next 10 years devoted time to maintenance and installation of multiple switchboards, lighting and power systems of central offices, toll switching, party line ringing, and simplex

telegraph and phantom equipment. In 1903 he was superintendent of fire and police telegraph systems, and served as chief inspector for enforcement of the National Electric Code, as well as supervising street lighting in the city of Omaha. In 1904 he became general superintendent of the U. S. Telephone and Telegraph Company, Waterloo, Iowa; and in 1905 he became general equipment foreman for the Nebraska Telephone Company, later becoming appraisal engineer for this organization. During this period he also was a member of the Nebraska State Railway Commission's committee for the development of telephone plant cost units. In 1909 he became division engineer in responsible charge of engineering plans, specifications, and estimates for all types of telephone plants. Subsequently he became engineer for the Northwestern Bell Telephone Company at Omaha, from which position he recently retired. Mr. Patton has served as member and treasurer of the Omaha and Council Bluffs Electrolysis Survey Committee, director and vice-president of the Omaha Technical Club, member and secretary of the Nebraska joint committee on physical relations between electric supply and signal lines, and organizing member of the Engineers' Club of Omaha. For the latter organization he has been director, treasurer, and president. He has served the Institute as vice-president of the North Central District 1931–33, and as a member of the communication committee 1932–33. Mr. Patton is a member of the Telephone Pioneers of America.

K. B. McEACHRON (A'14, M'20) lightning research engineer of the Pittsfield, Mass., works of the General Electric Company, has been promoted to engineer in charge of high voltage practice throughout the works. He will direct the activities of the high voltage engineering laboratory formerly in charge of the late F. W. PEEK, JR., (A'07, M'13, F'25, and director 1929–33). Mr. McEachron will correlate all lightning research work being carried on by various designing engineers in connection with apparatus development. He received the degrees of electrical engineer and mechanical engineer from Ohio Northern University in 1913, and the degree of M.S. in E.E. from Purdue University in 1920. In 1913 he entered the test department of the General Electric Company. Between 1914 and 1918 he was instructor in electrical engineering at Ohio Northern University, and between 1918 and 1922 was instructor in electrical engineering, research associate, engineering experiment station, Purdue University. In 1922 he was placed in charge of the research and development section of the lightning arrester department of the General Electric Company where his work has since been concerned with the study of natural and artificial lightning. He is the holder of a Coffin award for his development with 3 other engineers of the insulating material known as thyrite. He has conducted many pioneering studies with the cathode ray oscillograph, especially as applied to studies on actual transmission lines. He is the author of several papers presented before the Institute. His articles also have appeared frequently in the General Electric Review and foreign technical publications. Mr. McEachron has served the Institute as a member of its electrophysics committee 1926–32, and a member of the protective devices committee 1926–28.

K. B. McEACHRON

W. P. SCHWABE (A'96, M'24, and member for life) manager of The Northern Connecticut Power Company, Thompsonville, Conn., a subsidiary of Connecticut Electric Service Co., and who completed 25 years of service with the Company on Sept. 1st, 1933, has been notified by the Federal Home Loan Bank Board of Washington of his election as a director in the Federal Home Loan Bank of Boston for a term of 3 years beginning Jan. 1, 1934. He has taken an active interest in building and loan matters for a good many years. He is also president of The Thompsonville Building and Loan Association, president of Connecticut Building and Loan League, national Executive committeeman in the United States Building and Loan League. He is also now a director in the Federal Home Loan Bank, District No. 1, serving as one of the original appointees.

FRED S. HUNTING (A'92, M'93, F'13, and member-for-life) has returned from his retirement from business in California to accept the presidency of the Fort Wayne (Ind.) National Bank. Upon graduation from Worcester Polytechnic Institute in 1888, he entered the employ of the Fort Wayne Electric Company, and lived in Fort Wayne from that time until 1922. In 1911 he became general manager of the Fort Wayne works of the General Electric Company. In 1922, he became president of the Robbins and Myer Company at Springfield, Ohio; retiring from active business in 1927.

O. H. CALDWELL (A'13, M'22) editor of *Electronics*, and president of the New York Electrical Society, received the honorary degree of doctor of engineering from Purdue University November 4, 1933. Mr. Caldwell served as a member of the original Federal Radio Commission. He also is a director of the Institute of Radio Engineers, member of the communications and radio committees of the American Engineering Council, and trustee of the New York Museum of Science and Industry. He is a past-chairman of the Institute's New York Section.

H. G. HOWARD (A'08, M'25) formerly chief engineer of hydroelectric development, government of Madras (India) public works department is now chief engineer of the electricity department at Madras. Mr. Howard has just completed the Pykara hydroelectric undertaking. Formerly he was chief engineer of Cia Chilena de Electricidad, Santiago, Chile, and chief engineer of the Mexico Light and Power Company and Mexican Tramways Company.

H. L. RUSCH (A'24) who joined the organization of the Northern Pump Company, Minneapolis, Minn., a year and a half ago, has been elected vice-president of the company and appointed eastern sales manager. He formerly was supervisor of the technical data section and of the performance report section of the Johns-Manville Corporation, and prior to that time was eastern district manager for Arthur C. Nielsen, Inc. His headquarters will be in New York, N. Y.

R. N. CONWELL (A'15, F'31) transmission and substation engineer, Public Service Electric and Gas Company, Newark, N. J., has been appointed a representative of the Institute's committee on power transmission and distribution, on the American committee on marking of obstructions to air navigation. The other representative of the Institute on this committee is W. H. HARRISON (A'20, F'31) who previously had been reappointed to serve.

H. R. WOODROW (A'12, F'23) vice-president in charge of electrical operations for the Brooklyn (N.Y.) Edison Company, has been appointed to serve as a representative of the Institute on the board of trustees of United Engineering Trustees, Inc., for the 3-year term beginning January 1934. Mr. Woodrow succeeds H. A. KIDDER (A'06, F'29).

N. E. CANNADY (A'18, M'25) state electrical engineer, State of North Carolina insurance department, Raleigh, has been elected a member of the executive council of the International Association of Electrical Inspectors. Mr. Cannady also is chairman of the national electrical code standards committee of this organization.

H. N. PYE (A'15, M'27) chief engineer, Southeastern Underwriters Association, Atlanta, Ga., has been elected a member of the executive council of the International Association of Electrical Inspectors. Mr. Pye also is a member of the national electrical code standards committee of this organization.

H. L. WILLS (A'20) consulting engineer, Atlanta, Ga., and coördination engineer for the Georgia Power Company, has been elected a member of the Executive committee of the Southern Section, International Association of Electrical Inspectors.

M. W. BADEN (M'30) vice-president and director of research for The Trees Oil Company, Winfield, Kan., has resigned, and will open an office in Winfield to conduct a laboratory for research problems pertaining to the oil industry.

H. S. Broadbent (A'22) formerly commercial engineer for the Westinghouse Lamp Company, Bloomfield, N. J., has been appointed manager of the commercial engineering department of the company.

E. W. Judy (A'26) vice-president and manager of the Duquesne Light Company, Pittsburgh, Pa., has been elected a vice-president of the Pennsylvania Electric Association.

A. J. Althouse (A'11, M'29) general manager, Metropolitan Edison Company, Reading, Pa., has been elected a vice-president of the Pennsylvania Electric Association.

C. W. Taggart (A'26) general manager of the gas and electrical department of the city of Norwich, Conn., has relinquished these duties after 13 years of service.

Obituary

Herbert Hopkins Dewey (A'11) vice-president of the International General Electric Company, Inc., died at his home in Schenectady, N. Y., October 25, 1933, after a short illness. He was born in Lawrenceville, N. Y., in 1881. In 1899 he graduated from Potsdam State Normal School, and in 1904 from the St. Lawrence University. In 1907 he joined the testing department of the General Electric Company, and 2 years later was assigned to the power and transmission section of the power and mining department. He had charge of this section from 1916 to 1921. He was then made assistant engineer of the central station department when in 1921 the power and mining and the lighting departments were consolidated. In 1927 and again in 1928 he went to the U.S.S.R. for the company, and in 1928 he was appointed vice-president of the International General Electric Company with supervision of all interests of the company in connection with the U.S.S.R. business. Mr. Dewey had traveled extensively for the company, having visited Chile in 1919 in connection with engineering projects of the Chile Exploration Company of Antofogasta, and the Braden Copper Company of Santiago, and the city of Santiago, in connection with the study of hydraulic power in this vicinity. In 1921 he spent 8 months in Australia assisting in negotiations for electric equipment for the development and transmission of power from the brown coal fields of Victoria for the supply of Melbourne.

Charles Scott Thompson (M'26) consulting engineer, Oklahoma City, Okla., died in Oshkosh, Wis., August 2, 1933. He was born in Oshkosh in 1880. He spent 2 years in the general science course of the University of Wisconsin. Between 1901 and 1903 he was engineer at Oshkosh as a representative of the General Electric Company, and between 1903 and 1905 was engaged in erection work for the Chicago, Ill., office of the Stanley Electric Company. Between 1905 and 1912 he was in charge of all construction of the Central Construction Company, contractors and engineers at Oshkosh. While in this position he built several properties in the Middle West. In 1913 he joined the Central Illinois Public Service Company as engineer in charge of construction of power plants, substations, and other plants, under the general supervision of Sargent and Lundy. Between 1914 and 1919 he was chief engineer for William and S. Mainland, at Oshkosh. In 1919 he undertook construction, operation, and general engineering and executive duties for the properties of the Shawnee Gas and Electric Company, the Ada Electric Company, the Holdenville Electric and Gas Company, and about 10 smaller plants. He also designed and constructed other properties, all owned now by the Oklahoma Gas and Electric Company. Since 1919 he has practiced consulting engineering and has given most of his time to valuation and rate making. Since 1924 he has lived in Oklahoma City.

Charley Gould Beckwith (A'08) electrical engineer and general superintendent, municipal electric light department, city of Cleveland, Ohio, died September 28, 1933. He was born in Dowagiac, Mich., in 1870. He studied electrical engineering at the University of Michigan, Ann Arbor, and upon leaving the university in 1892 entered upon a career of building and operating electric light plants. He built and operated a small municipal plant in Cassopolis, Mich., and later in Jonesville, Mich. From there he went to Montpelier, Ohio, where he operated a plant for 6 years. In 1900 Collinwood, Ohio, decided to build a municipal light plant, and Mr. Beckwith constructed this plant and operated it for 7 years. Collinwood was annexed to Cleveland in 1910, and Mr. Beckwith became an employee of the city as superintendent of the municipal plant. He was made general superintendent 2 years later and held that position until his death. Early in his career, Mr. Beckwith became interested in street lighting and it is reported that as a result of his researches Cleveland was the first city in the country to use the tungsten lamp for street lighting. He also was an expert in rate structures.

Horace Woelfkin Steinhoff (A'22) died July 28, 1933. He was born in New York, N. Y., in 1901. He studied electrical engineering at the University of Pennsylvania. His first employment where he was brought in contact with electrical work was at the plant of the Lake Torpedo Boat Company, Bridgeport, Conn., where he spent 2 years during the war. He began as a helper, and was switchboard operator in the power house when he left to attend the University of Pennsylvania. Upon leaving the university he took a position with the Western Electric Company as relay inspector. Subsequently he was for several years consulting engineer for the Stanley-Warner Theater Company, and was chief engineer for Fox Theaters, Inc. Recently he had been in the construction business for himself.

Membership

Recommended for Transfer

The board of examiners, at its meeting held November 15, 1933, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Hamann, Adolf M., chief engr., E. I. du Pont de Nemours & Co., Niagara Falls, N. Y.
Kouwenhoven, Wm. B., prof. of E.E. & asst. dean, Sch. of Engg., Johns Hopkins Univ., Baltimore, Md.

To Grade of Member

Angus, D. J., chief engr. and treas., Esterline Angus Co., Indianapolis, Ind.
Carpenter, R. B., branch mgr., Southern Pub. Util. Co., Thomasville, N. C.
Conney, Wm. H., designing engr., Gen. Elec. Co., Pittsfield, Mass.
Cora, Charles A., gen. commercial engr., Indiana Bell Tel. Co., Indianapolis.
De Lanty, B. P., gen. mgr., Municipal Lt. & Pwr. Dept., Pasadena, Calif.
Dundatscheck, Louis, div. equip. engr., N. Y. Tel. Co., New York.
Gilkeson, C. L., asst. engr., Edison Elec. Inst., New York.
Jarvis, K. W., dir. of engg., Zenith Radio Corp., Chicago, Ill.
Mackeown, S. S., asso. prof. of E.E., Calif. Inst. of Tech., Pasadena.
Montrose, F. A., vice-pres., and gen. mgr., Indiana Bell Tel. Co., Indianapolis.
Reynolds, H. L., sales engr., Allis-Chalmers Mfg. Co., Dallas, Texas.
Rossi, Ralph T., engr. in charge of constr., R. C. A. Communications, Inc., New York.
Schmid, C. F., engr., cable engg. dept., Anaconda Wire & Cable Co., Hastings-on-Hudson, N. Y.
Snow, Wm. B., member of tech. staff, Bell Tel. Labs., Inc., New York.
Wayne, J. Lloyd, 3d, gen. toll supervisor, Indiana Bell Tel. Co., Indianapolis.

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before December 31, 1933, or February 28, 1934, if the applicant resides outside of the United States or Canada.

Angst, G., Gen. Elec. Co., Lynn, Mass.
Atwater, DeN. W., Westinghouse Lamp Co., Bloomfield, N. J.
Bernarde, H. L., Westinghouse Elec. & Mfg. Co., Newark, N. J.
Boadway, C. W., Hydro Elec. Pwr. Comm. of Ont., Toronto, Ont., Can.
Brown, M. W., Pub. Ser. Co. of Indiana, Edinburg.
Brown, N. H., Hydro Elec. Pwr. Comm., Toronto, Ont., Can.
Burrin, T. J., Pub. Ser. Commission of Indiana, Indianapolis.
Carroll, J. F., Indiana Bell Tel. Co., Indianapolis.
Cobb, L. M., Seward-Hamilton Garage, Inc., Detroit, Mich.
Davis, J. R., Stanton Operating Co., West Pittston, Pa.
Ellerbe, E. B., Westinghouse Elec. & Mfg. Co., Wilkes-Barre, Pa.
Fowler, N. B., Am. Tel. & Tel. Co., Atlanta, Ga.
Fritz, E., Pa. Water & Pwr. Co., Baltimore, Md.
Gregory, E. J., Wis. Steel Co., Benham, Ky.
Gregory, T. G., 516 Sutter St., San Francisco, Calif.
Guerrieri, J., 20 Christopher St., N. Y. City.
Herrity, J. J., Bradley Co., Phila., Pa.
Iskiyan, H. S., Jr., Rockefeller Center Inc., N. Y. City.

Keddy, F. B., United Elec. Lt. & Pwr. Co., New York, N. Y.
Kimberly, E. E., Ohio State Univ., Columbus.
King, H. F., Mass. Inst. of Tech., Cambridge.
Lynch, E. M. (Member), Florida Pwr. Corp., St. Petersburg.
Markarian, P. B., Scranton Elec. Co., Scranton, Pa.
McDougall, S., Am. Tel. & Tel. Co., Denver, Colorado.
Miller, S. C., Chesapeake & Potomac Telephone Co. of Baltimore City, Baltimore.
Mucci, J. R., 145 Oakland St., Malden, Mass.
Newmeyer, W. L., Jr. (Member), U.S. Reclamation Bureau, Denver, Colo.
Pearce, W. B., Shell Eastern Petroleum Products, Inc., Revere, Mass.
Richards, A. F., Stanton Operating Co., Pittston, Pa.
Schoch, C. L., N. J. Bell Tel. Co., Newark, N. Y.
Shimer, W. B., Schwitzer-Cummins, Indianapolis, Ind.
Stoddard, R. N. (Member), Westinghouse Elec. & Mfg. Co., Shell Pittsburgh, Pa.
Stroppel, R. E., The Tool Steel Gear & Pinion Co., Cincinnati, Ohio.
Suher, Abe, 11 Taft St., Springfield, Mass.
Whitman, W. C., Narragansett Elec. Co., Providence, R. I.
Woods, F. L., Gen. Elec. Co., Pittsfield, Mass.

36 Domestic

Foreign

Affleck, W. E. (Member), Corp. Elec. Works, Guildford, Surrey, Eng.
Hoe, T. G., c/o Messrs. Seng Lee & Co., Penang, Straits Settlements.
Khosla, R. N. (Member), Gaya Engg. & Elec. Pwr. Sup. Co. Ltd., Gaya, India.

3 Foreign

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Blackhall, Harold J., Postlagernd, Essen, Germany.
Boicourt, Frank R., Rockwell City, Iowa.
Bugnion, Frank E., 14 Clinton St., Cambridge, Mass.
Code, F. L., 6061 Trafalgar St., Vancouver, B. C., Can.
Endicott, E. M., 2020 Monroe St., Toledo, Ohio.
Ghamat, S. B., School of Engg. of Mil., Milwaukee, Wis.
Hamby, H. M., 708 F St., N.E., Washington, D. C.
Hirsch, Chas. J., Level Club Hotel, 253 W. 73rd St., N. Y. City.
How, John H., 42 Wai Oi Road East, Canton, China.
Kahale, N. A., Box 434, W. Lafayette, Ind.
Lober, Charles, K. C. P. & L. Co., 1330 Baltimore Ave., Kansas City, Mo.
McDonnell, John D., Box 691, Burlington, N. C.
Stroemer, 7229 Penn Ave., Pittsburgh, Pa.
Talbot, H. L., 55 Pine Ave. E., Montreal, Que., Can.
Weber, George A., 537 Addison Ave., Palo Alto, Calif.

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, during October are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface or text of the book in question.

DESIGNING for ARC WELDING, Second Lincoln Arc Welding Prize Competition Papers. Edit. by A. F. Davis. Cleveland, Ohio, Lincoln Elec. Co., 1933. 424 p., illus., 9x6 in., cloth, $2.50. Contains 10 of the papers submitted in the second Lincoln arc welding prize competition. All deal with the use of arc welding in the design of machines or structures, and illustrate novel applications of the process. The papers included show applications to machinery, ships, buildings, bridges, large containers, pipes and pipe fittings.

ELECTRICAL PROPERTIES of GLASS. By J. T. Littleton and G. W. Morey. N. Y., John Wiley & Sons, 1933. 184 p., illus., 9x6 in., cloth, $3.00. The third monograph issued under the auspices of the committee on electrical insulation of the National Research Council affords a convenient summary of our knowledge of the electrical properties of glasses. The existing data upon the physical and chemical properties of glasses and upon their electrical conductivities and dielectric properties are presented and reviewed critically. The work is primarily a reference book for laboratory workers, but some attention is given to the use of glass as an engineering material.

HANDBOOK of the COLLECTIONS ILLUSTRATING ELECTRICAL ENGINEERING. I. ELECTRIC POWER, Pt. 1.—History and Development. By W. T. O'Dea. Lond., So. Kensington Science Museum, 1933. 78 p., illus., 10x6 in., paper, 2s 6d. The history of the generation, transmission, and industrial uses of electric power is outlined concisely in this handbook, which is intended primarily as a guide to the exhibits in the Science Museum, South Kensington, London.

LIQUID DIELECTRICS. By A. Gemant, translated from the German by V. Karapetoff. N. Y., John Wiley & Sons, 1933. 185 p., illus., 9x6 in., cloth, $3.00. A correlative survey of the general physics of liquids as related especially to their behavior as dielectrics. The essential mechanical and thermal properties, the physico-chemical behavior, the electrical and optical properties, and the behavior in intense fields of liquid dielectrics are described, and their more important applications to electrical engineering considered. Issued under the auspices of the committee on electrical insulation of the National Research Council.

POWER SALES. By D. Taylor. N. Y. & Lond., McGraw-Hill Book Co., 1933, 206 p., tables, 8x5 in., cloth, $2.00. This book, an outgrowth of articles in the *Electrical World*, discusses problems met in extending central-station power service, and gives many suggestions for solving them. The author is sales supervisor of the Utility Management Corporation.

PRINCIPLES and PRACTICE of ELECTRICAL ENGINEERING. By A. Gray, rev. by G. A. Wallace. 4 ed. N. Y. & Lond., McGraw-Hill Book Co., 1933. 538 p., illus., 9x6 in., $4.00. Intended primarily for engineering students who were not specializing in electrical engineering. The present edition has been completely rewritten. Emphasis is directed toward the fundamental theory and the subject is developed by elaborating the basic principles rather than by solving mathematical equations.

RAYLEIGH'S PRINCIPLE and Its Applications to Engineering. By G. Temple and W. G. Bickley. Lond. & N. Y., Oxford Univ. Press, 1933. 156 p., illus., 9x6 in., cloth, $4.50. Intended to familiarize engineers with the utility of Rayleigh's energy method for the rapid, direct calculation of the approximate values of critical loads and speeds. The method is developed in such a way as to furnish both upper and lower estimates of the true value required, so that it enables critical loads and frequencies to be determined with close, known degrees of approximation.

(1933) A.S.T.M. MANUAL on PRESENTATION of DATA with Table of Squares and Square Roots, sponsored by Committee E-1 on Methods of Testing. Phila., Am. Soc. for Testing Materials, 1933. 45 p., illus., 9x6 in., paper, $.50. Discusses application of statistical methods to the problems of condensing a set of observations and presenting the essential information in a concise, readily interpretable form. The report is the work of a committee of engineers who are expert statisticians.

A.S.T.M. STANDARDS on ELECTRICAL INSULATING MATERIALS, prepared by Committee D-9 on Electrical Insulating Materials, Sept., 1933. Phila., Am. Soc. for Testing Materials. 242 p., illus., 9x6 in., paper, $1.25. All the specifications and test methods of the Society which relate to insulating materials are brought together in this volume. The report of the committee on the subject is also included, with its recommendations for changes.

ANHALTSZAHLEN für den ENERGIEVERBRAUCH in EISENHÜTTENWERKEN. (Wärmestelle Düsseldorf). Edit. by Verein deutscher Eisenhütteneute. 3 ed. Düsseldorf, Verlag Stahleisen, 1931. 119 p., illus., 12x8 in., cloth, 16 rm. A compilation of data relating to heat and power consumption in iron and steel works. The data cover fuels, coke-oven operation, blast furnaces, open-hearth, bessemer and electric steel works, melting-furnaces, gas producers, mill furnaces, rolling-mills, engines, etc.

Engineering Societies Library

29 West 39th Street, New York, N.Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

CONGRÈS INTERNATIONAL D'ÉLECTRICITÉ, Paris, 1932. 13 Vols. Comptes Rendus. Paris, Gauthier-Villars, 1933. Illus., 10x6 in., cloth (1,000 frs. entire set). V. 1, 85 frs.; v. 2, 135 frs.; v. 3, 110 frs.; v. 4 & 5, 180 frs.; v. 6, 105 frs.; v. 7, 65 frs.; v. 8, 60 frs.; v. 9, 55 frs.; v. 10, 80 frs.; v. 11, 65 frs.; v. 12, 85 frs.; v. 13, 70 frs. The *Proceedings* of the Paris, 1932, International Electrical Congress are now available in 13 large volumes, substantially bound. V. 1, general information, gives a list of the delegates and the proceedings of the sections, etc. V. 2 contains the papers on general theory; 3, measurements; 4 and 5, production and transformation of electric energy; 6, transmission and distribution; 7, electric traction; 8, lighting and radiology; 9, electrochemistry and electrometallurgy; 10, communication by wire; 11, high frequency phenomena; 12, atmospheric electricity, terrestrial magnetism, history of electrical engineering, teaching; 13, miscellaneous applications. The volumes may be purchased separately at reasonable prices.

ELECTRICAL CONCEPTIONS of TODAY. By C. R. Gibson. Lond., Seeley, Service & Co., Ltd., 1933. 284 p., illus., 8x5 in., cloth, 6s. The experiments which form the basis for recent ideas about atoms, electrons and other matters relating to electricity are described and their significance explained for laymen. An inexpensive reprint of "Modern Conceptions of Electricity," published in 1928.

ELEMENTS of HEAT-POWER ENGINEERING, Pts. 2 and 3. By W. N. Barnard, F. O. Ellenwood and C. F. Hirshfeld. 4 ed. N. Y., John Wiley & Sons, 1933. 1200 p., illus., 9x6 in., cloth, Pt. 2, $5.50; Pt. 3, $4.50. These volumes complete this work which, in addition to its value as a textbook, is well suited for reference use. V. 2 discusses steam-generating apparatus and prime movers, fuels, combustion, and heat transmission; v. 3, auxiliary equipment, the power-plant ensemble, air conditioning and refrigeration.

EXPERIMENTAL ELECTRICAL ENGINEERING and MANUAL for ELECTRICAL TESTING, v. 1. By V. Karapetoff, rev. by B. C. Dennison. 4 ed. N. Y., John Wiley & Sons, 1933. 781 p., illus., 9x6 in., cloth, $6.00. A laboratory manual for students and engineers. Presents material actually taught in this country. The present volume contains the tests of a general character usually called for, more advanced tests being contained in the second. This edition has been thoroughly revised.

GRUNDLAGEN des ELEKTRISCHEN SCHMELZOFENS. Elektrische Gesetzmässigkeiten, Bauliche Gliederung, Energiehaushalt. (Monographien über angewandte Elektrochemie, v. 52). By J. Wotschke. Halle (Saale), Wilhelm Knapp, 1933. 505 p., illus., 9x7 in., paper, 42 rm.; bound, 44 rm. The electrical laws governing electrical metallurgical furnaces, the structural types in use and the economics of electric smelting are discussed in the light of actual installations for various purposes. The book aims to present the common principles which govern the slection of equipment for any given use.

RADIO CONSTRUCTION and REPAIRING, including the Television Receiver. By J. A. Moyer and J. F. Wostrel. 4 ed. 448 p., illus., 8x5 in., cloth, $2.50. For the amateur builder and the repair man. Directions are given for building several types of receivers, including one for television, together with detail instructions for diagnosing and remedying defects in reception. Recent developments in vacuum tubes and design have made this revision desirable.

Industrial Notes

C. R. Myer Elected General Cable V-P.—According to a recent announcement, C. R. Myer was elected vice-president of the General Cable Corporation at the last meeting of its board of directors.

"Three-Light" Lamps.—To meet a need for greater flexibility of illumination from lighting installations, the Westinghouse Lamp Co. is introducing a twin-filament lamp in two sizes. They are to be known as the "Three-Light" lamps and will produce three different wattages. The Mazda 150–200 watt lamp in a PS-35 bulb will consume 150, 200, or 350 watts, and the 200–300 watt lamp in a PS-40 bulb will consume 200, 300, or 500 watts. Both lamps are designed with inside-frost bulb and will operate on either 110, 115, or 120 volt circuits.

Oil-Blast Breakers.—A new line of outdoor oil-blast circuit breakers, designated as type FKO-127 and recommended for station and rural distribution service, has been developed by the General Electric Co. The new breakers are of the rectangular-tank type and may be operated manually or electrically. The equipment is suitable for either pole or framework mounting. Despite their compactness, the breakers have liberal margins of safety, all ratings having been verified by complete tests. They are rated: 400 and 600 amperes at 7500 volts with an interrupting rating of 50,000 kva.

Outdoor Automatic Step-Voltage Regulator.—A new automatic step-voltage regulator, particularly applicable for maintaining constant voltage on suburban and rural circuits of 4,800 volts or more, and for regulating low-voltage high current city distribution feeders where the service will permit, is announced by the Westinghouse Electric and Mfg. Co. The new type UR regulator is available in either single or polyphase design for 10% regulation with 17 points of $1^1/_4$% steps or 33 points of $^5/_8$% steps. It consists of a regulating auto-transformer and a load tap changer built into an integral unit arranged for outdoor operation. Regulation of the circuit is accomplished by changing taps under load on the regulating auto-transformer.

New Open Fuse Cutout.—A new open fuse cutout announced by the General Electric Co. incorporates a drop-out feature which gives the lineman positive indication that the fuse has been blown and the circuit opened at that point. A new fuse link can be quickly and easily installed. The fuse holder can be removed or installed with a standard switch hook. The weather-resistant fuse-holder tube can be renewed without replacing the metal parts and an automatic latch prevents the fuse holder from falling out of the support during the expulsion recoil. The new cutout is available in two voltage ratings, 7,500–12,500V and 15,000 volts. Both can be fused from one to 60 amperes, and have 1,200 ampere interrupting capacity.

Conversion Parts for Radio Transmitters.—In line with its policy of making latest improvements available to owners of its apparatus, the Western Electric Co. has produced a set of conversion parts for its 6 type (5 kilowatt) radio broadcast transmitters. This equipment, in addition to eliminating motor generators, will increase the modulation capability of transmitters of this type to 100 per cent by increasing the plate voltage applied to the last radio frequency power amplifier from 4,000 volts to 5,000 volts. The essential unit in the set is a 5,000 volt mercury vapor rectifier which replaces the existing 2,000–4,000 volt motor generator. The 5,000 volt supply permits operation of the final power amplifier tube of the transmitter at that part of its characteristic which allows full use of its capacity to pass all the power required for 100 per cent modulation, with an attending audio harmonic content well within the requirements of the Federal Radio Commission. Eliminating the generator also increases dependability and ease of maintenance. The conversion requires only minor changes in the transmitter. Operation remains virtually unchanged.

Trade Literature

Motors.—Bulletin, 12 pp. Describes a comprehensive line of motors, generators, motor generator sets, and speed changers. Crocker-Wheeler Electric Mfg. Co., Ampere, N. J.

Machine Tool Motors.—Bulletin 174, 4 pp. Illustrates applications of totally-enclosed, fan-cooled motors to milling, drilling, grinding and other machine tools, from the smallest to the largest sizes. Wagner Electric Corp., 6400 Plymouth Ave., St. Louis, Mo.

Zinc.—Bulletin, 24 pp. on "Planning, Making, Selling—Design for Profit." Illustrates the application of zinc and alloys in the products af many industries. The New Jersey Zinc Co., 160 Front St., New York.

Screws and Bolts.—Catalog, 104 pp. Includes detailed and general information on screws, bolts, nuts, and allied products. Gives reference tables on standard screw threads and tolerances. Pheoll Mfg. Co., 5700 Roosevelt Rd., Chicago, Ill.

Motor Chart.—Bulletin. Comprises a comprehensive motor application chart, illustrating 29 different types of electric motors and listing the proper motor for over 50 different standard applications. The Louis Allis Co., Milwaukee, Wis.

Aluminum Welding.—Bulletin, 42 pp., The Welding of Aluminum. Describes correct application of different classes of welding to aluminum and its alloys. Riveting.—Bulletin, 26 pp. Describes the proper methods of joining aluminum by the riveting process. Aluminum Company of America, Pittsburgh, Pa.

Instrument Transformers.—Bulletin Ms IV/e. Describes a complete line of portable instrument transformers of the precision type available for use on higher voltages than generally offered on transformers of this kind. Precision potential transformers in ranges from 1 to 15 kv are also described. Herman H. Sticht & Co., 27 Park Pl., New York.

Transformers.—Bulletin, 4 pp. Lists various types of Ferranti transformers and chokes, applicable in the communication field, including those employed in connection with the more commonly used types of new vacuum tubes introduced in the past year. The company has expanded its facilities for the design and production of quality iron core products. Ferranti Incorporated, 130 West 42nd St., New York.

Pintype Insulators.—Bulletin 603H, 32 pp. Describes the complete line of O-B pintype insulators, strain insulators, fittings and pins. The book includes an interesting treatise on the design of pintype insulators. In addition, a new development in strain insulator fittings is outlined. The catalog numbers assigned to O-B insulators having larger top grooves are shown along with insulator characteristics such as mechanical strength, wet and dry flashover values, wet and dry leakage distances. Pin-hole data and recommended pin lengths are also given. Discussions pertaining to field problems encountered in the construction of pintype lines are a part of the bulletin. Ohio Brass Co., Mansfield, O.

Machinery Mountings.—Bulletin G-1, 60 pp. Describes Kingsbury propeller shaft thrust bearings used in vessels of all sizes and for horizontal thrusts in heavy industrial machinery of various kinds. Engineering data is given for applications of new standard thrust bearing and journal bearing mountings for horizontal shafts, ranging from $2^3/_4$ inches to $23^1/_4$ inches diameter. The Kingsbury thrust bearing, widely known in marine and public utility fields, carries its load on oil films formed over pivoted shoes that are copiously lubricated. Kingsbury Machine Works, Inc., 4320 Tackawanna St., Philadelphia, Pa

Relays.—Bulletin P-41. Describes the Dunco polarized relay, designed for operation where the direct current in the operating coils must be kept as low as possible, and where a reversal of the current in the operating coils brings about a reversal in the contact arrangement, but where no contact is made when the coils are deenergized. It consists of a permanent magnet and two coils arranged to give a push-pull effect on the armature carrying the moving contacts. The strength of the permanent magnet is adjustable by a movable shunt. The position and tension on the moving contact member are adjustable, and the fixed contacts are also adjustable. This unit is one of a large variety of polarized relays now being built by this company for special applications. Struthers Dunn, Inc., 139 N. Juniper St., Philadelphia, Pa.